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EXPERIMENTAL TRANSMITTING AND RECEIVING EQUIPMENT FOR HIGH-SPEED FACSIMILE TRANSMISSION

I. GENERAL

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by H. RINIA, D. KLEIS and M. van TOL.

In recent years a new system has been developed at Eindhoven for facsimile transmission and reception of drawings, photographs or printed matter capable of transmitting a document of quarto size (21 cm × 29.7 cm) in 8 seconds by means of a cable or by radio. The system is continuous: the documents, the size of which — apart from a limit on the width of 22 cm — is immaterial, are placed on an endless belt upon which they are electrically "stuck" for scanning by a rapidly rotating optical system. At the receiving end positive or negative reproductions, reduced 6 × in size, are "written" on a continuously moving film which then passes through the developing and fixing processes and can if necessary be printed immediately on sensitized paper, enlarged to the original size. The resolving power of the system is 5 lines per mm, which corresponds to the best reproduction obtainable from the older and slower types of equipment. A number of characteristic features and possibilities of application of the new system are reviewed in this article; a description of the mechanism, with details of the optical and electrical devices, will be presented in subsequent articles in this review.

In 1843, when Morse telegraphy was still in its infancy, a British physicist, Bain, demonstrated an apparatus by means of which it was possible to reproduce hand-written characters at a distance, over an electric circuit. In 1865 Caselli carried out in France a number of experiments with this so-called facsimile telegraph, which was then capable of handling 600 written words per hour. Around the year 1890 numerous other experiments in this direction were carried out in the United States and by 1907 a whole network was employed for a short time in Europa for the telegraphic transmission of illustrations for the daily press. After the first world war, mainly between 1922 and 1928, a number of facsimile systems were developed, incorporating considerable technical improvements [1]) and the resultant installations appeared to have come to stay. Since then, facsimile networks in Europa and America were extended more and more and permanent inter-continental connections were subsequently established: in 1931 there were more than 25 European stations in use, whilst by 1937 London was maintaining permanent picture-telegraph communication with many European capitals, as well as with New York, Buenos Aires and Melbourne.

This short and by no means comprehensive historical sketch is intended merely to show that facsimile transmission has for a long time occupied a definite place in the field of telecommunications, to supplement the well-established Morse telegraphy, telephony, teleprinting and — the latest acquisition to this family — television.

There can, in fact, be no doubt that in many spheres of application the possibility of transmitting documents and pictures in facsimile, by cable or radio, furnishes an essential adjunct to the conventional transmission of words, whether spoken or recorded in the form of standardised characters. The contents of a letter can thus be transmitted telegraphically without depriving it of its most individual character, the handwriting of the sender; a cheque, complete with signature, can

1) Among the more important systems at this time were those of Korn, 1922; Bartlane, 1922; Belin, 1924; Jenkins, 1924; American Tel. and Tel. (Bell system), 1924/5; RCA (Ranger), 1924/5; Siemens Karolus Telefunken, 1927; Westinghouse (Zworykin), 1928.

be reproduced for examination at places far removed from the point of origin within a matter of minutes only; technical drawings, details of which cannot be clearly expressed in words; weather charts showing the changes in meteorological conditions hour by hour; press-photographs; texts in languages not employing the letters of the alphabet, such as Chinese — these are but a few examples of the objects for which of picture transmission is the indicated method.

Efforts have recently been made in various quarters to create a still wider scope for facsimile transmission in our daily life, and developments are actually in progress in two different directions, viz.

1) In the United States a wider field is being sought for facsimile transmission in the form of a supplementary feature in broadcast transmissions, using relatively simple facsimile receivers, based on the systems of Finch, Hogan or Alden, which can be connected to any ordinary radio receiver in place of the loudspeaker. Listeners are thus to be provided in their own homes with a radio news-sheet containing actual photographs as well as many other items of visual interest. Endeavours are also being made to arouse interest in facsimile transmission for mobile services such as the police, fire brigade, taxis and aircraft, for the transmission of situation diagrams and written orders (also finger-prints etc. for the police) to and from headquarters; the pictures are recorded automatically and it is claimed that facsimiles are less liable to be misunderstood than verbal messages.

2) The other line of development is directed towards a speeding-up of the transmission itself and, with it, an intensification of the facsimile traffic between any two fixed stations. As far back as 20 years ago attempts in this direction were made by Alexanderson [2]) and Zworykin [3]), but these did not meet with any permanent success. It seems to us, however, that this failure should be looked upon as being analogous to the initial fate of the ordinary "slow" facsimile technique; the network installed in 1907 and referred to above very quickly disappeared from the scene. The years from 1924 onwards saw a more permanent establishment of "slow" facsimile telegraphy networks, partly owing to the improved picture quality and more reliable working, but partly also to the greater demand for this means of communication. It is obvious that the intensification of facsimile traffic by high-speed equipment will likewise become a fact only when the various favourable conditions mentioned above have been realized.

With this in mind, and after preparatory work which has taken some years to complete, Philips have developed in their laboratories at Eindhoven a new system of high-speed facsimile transmission in which the use of recent technical advances guarantees not only high quality of reproduction but also great reliability in performance. It may be expected that, in view of the present pattern of our social structure, the possibilities offered by the new system will open up fresh and very important applications.

In presenting a series of articles in this journal, giving a description of the new facsimile system, we begin with a review of its fundamental principles and major characteristics, followed by a brief resumé of some of its possible fields of application. Later articles will then deal with the construction of the transmitter and the receiver, the optical system, the electrical transmission circuits and, finally, the synchronisation of receiver and transmitter.

Salient features of the new system

In accordance with the system employed in all present-day facsimile transmission equipment, the picture to be transmitted is scanned by a spot of light which traverses narrow, parallel and contiguous lines; the amount of light reflected (or transfused), which varies according to the local blackness of the picture, is transformed by means of a photo-electric cell into a varying electrical voltage, the image-signal, which is transmitted to the receiver via a cable or by radio. In the receiver this signal may be used to control the intensity of a beam of light which moves synchronously with the scanning spot at the transmitting end, and "writes" the successive lines on a sheet of sensitized material, the varying intensity of the light reproducing faithfully the pattern of light and shade in the original.

The smaller the spot of light used for the scanning (and reproduction), the better the quality of the reproduced image; in the Philips equipment the diameter of the scanning spot in the transmitter is *1/5th of a millimetre,* so that, in principle, it is possible to reproduce details of that order of size. This corresponds to the best reproduction so far achieved by any of the slower picture-telegraph systems. For purposes of comparison, details of the "resolving power" of various other methods of

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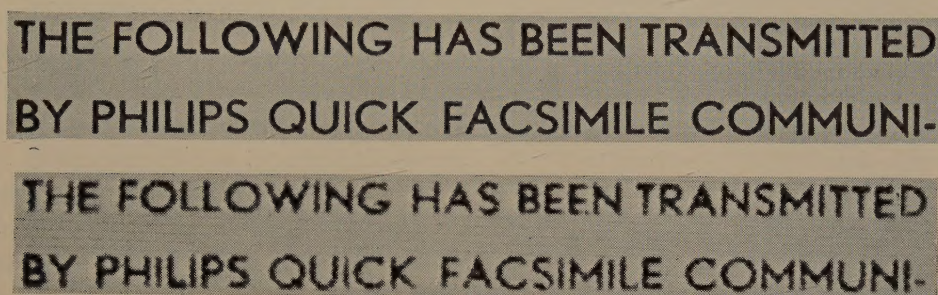
[2]) See, inter alia, F. Schröter, Handbuch der Bildtelegraphie und des Fernsehens, Springer, Berlin, 1932, p. 414.
[3]) V. K. Zworykin, Facsimile picture transmission, Proc. Inst. Rad. Eng. 17, 563-550, 1929.

reproduction are given in *table I* [4]). *Fig. 1* illustrates part of a document transmitted by the new Philips system.

Table I. Resolving power, in lines per mm, of various reproduction methods.

Newspaper picture	2-4
Half-tone blocks Philips Technical Review	6
Ordinary slow facsimile transmission (105 lines per inch)	4
Philips high-speed facsimile system	5
Photographic reproduction on positive film	55

The new system is capable of handling documents up to a width of about 22 cm, i.e. the maximum width of conventional letter paper, and of any length. A sheet of quarto size (roughly the size of 210:0.2 ≈ 1000 image elements. Thus, 1.5×10^6 elements have to be transmitted in eight seconds, which, in the extreme case of the successive elements being alternately black and white, corresponds to 200,000 luminous fluctuations per second, or a *maximum modulation frequency of 100 kc/s*. A frequency band of such a width is available with ultra-short-wave transmitters, which are frequently used for permanent beam-communication between two stations. Similar bandwidths are usually also available in present-day cable networks for carrier telephony; the network in the Netherlands, for instance, even permits of modulation frequencies up to around 200 kc/s. For the rest, the limit of 100 kc/s is not so very critical in actual practice, since tests have shown that signals from our equipment, transmitted over a line allowing a


a)
THE FOLLOWING HAS BEEN TRANSMITTED
BY PHILIPS QUICK FACSIMILE COMMUNI-

b)
THE FOLLOWING HAS BEEN TRANSMITTED
BY PHILIPS QUICK FACSIMILE COMMUNI-

Fig. 1. Part of a document transmitted by the new high-speed facsimile system: *a*) the original; *b*) the facsimile. Both *a*) and *b*) have been enlarged to twice the size of the actual original: owing to the enlargement the effect of the blurring of the printing block (see table I) on the image quality is eliminated. For a fair comparison, the text should be observed from a distance of about 50 cm (twice the normal reading distance). The time required for transmitting the area shown in this example is about 0.06 sec.

this page) 29.7 cm in length is *transmitted in 8 seconds*, whereas the more common facsimile systems require something like 8 minutes to reproduce a sheet of the same size (in some cases less, e.g. 2 to 3 minutes, but in many other cases still longer, viz. 20 minutes).

The number of image elements (that is, surface elements of the same size as the scanning spot) that can be transmitted per second over a given channel of communication is directly related to the maximum permissible modulation frequency in that channel. In our case, where the diameter of the spot is 0.2 mm, a sheet of the size on which this article is printed will contain 297:0.2 ≈ 1500 lines for scanning, and on each line there will be maximum modulation frequency of 80 kc/s, still give reproductions of quite reasonable quality. In the event that the modulation frequency has to be still further limited, the transmission rate can be reduced accordingly, to maintain the same resolving power. For this purpose the speed of both the transmitter and the receiver must be reduced, which can quite easily be achieved with the synchronisation method employed.

It is a well-known fact that in ordinary telegraphy the total quantity of information (number of characters coded according to a given system) capable of transmission per unit of time is, theoretically, roughly proportional to the width of the available frequency band, irrespective of the type of equipment employed [5]). Similar considerations apply to facsimile telegraphy, the total quantity of "information" being represented here by the number of picture elements. In connection with this fact, three remarks have to be made. Firstly, for the performance of a facsimile system, the frequency band (that

[4]) The obvious course would be to include in our comparison the reproduction obtained in television, but in judging television pictures other criteria are involved, since we are then dealing with moving images. Moreover, these images are viewed at much greater distances than ordinary correspondence or newspaper photographs, in just the same way as, in the cinema, the distance is such that the whole of the picture can be observed without moving the eye.

[5]) See e.g. J. te Winkel, Carrier Telegraphy, Philips Techn. Rev. 8, 206-213, 1946.

is, the number of picture elements that the equipment is capable of transmitting per second) is a better criterion than the actual area of picture transmitted per second, seeing that a given area could easily be transmitted more rapidly in a certain frequency band if one were contented with fewer lines per mm (e.g. if a larger scanning spot were used).

Secondly, with an ordinary facsimile system working 60 times more slowly than ours it is possible, for the same image quality and using a frequency band of 100 kc/s, to transmit roughly the same picture area per minute, provided the available band is divided into 60 channels, 60 transmitters and receivers being used. Needless to say, this would be far too cumbersome and uneconomical for a permanent link between any two given stations.

In the third place it is quite possible, in principle, to transmit documents by television, by photographing the image appearing on the screen, but, as the primary object of television is to transmit moving images, necessitating the transmission and reception of single images (of, say, 567 lines) in about 1/25 second, it requires an even much wider frequency band, namely 2000 to 3000 kc/s. The use of a frequency band of this width for facsimile work would be quite uneconomical at anything less than 20 to 30 times the speed of our new facsimile system. Whereas we consider that the speed of the Philips system will in many cases meet a practical demand, it seems doubtful whether a system working at a speed still 20 times higher would find regular employment. Furthermore, in order to be able to feed the documents into the machines fast enough, a film would first have to be made at the transmitting end, thus considerably complicating the process. Moreover the problem of the sensitivity of the recording material, which, as we shall see, played a very important part in the designing of our facsimile system, would be almost incapable of solution at very much higher speeds.

Any increase in the width of the frequency band employed is accompanied by a corresponding increase in the noise produced by fluctuations in the emission of electrons from the photocell and by the movement of the electrons in the resistor used for coupling the photocell to the amplifier. In our high-speed facsimile transmission, therefore, the noise level, taken absolutely, will be higher than in the slower systems; in spite of this, interference-free reproduction is assured by using a photocell with secondary emission amplification (electron-multiplier). The internal amplification of these valves may be of the order of 100,000, and the noise originating from the resistor in question is thus rendered quite negligible, whilst the apparatus itself is considerably simplified. In our case a *signal-noise ratio of 43 db* has thus been obtained, which is even better than with the majority of slow facsimile systems.

In the conventional, slower systems, scanning of the document is effected by wrapping it around a drum which rotates while an optical system slowly travels along the drum in the axial direction. The few seconds required to place a fresh document on the drum (or to replace the latter by another which has been previously loaded), do not make much difference to a transmitting time of several minutes per document, but in a system such as the one under review, in which the transmission time is a few seconds only, such repeated interruption of the transmission would be very prejudicious to the efficiency of the whole system; we have therefore made a departure from the now almost traditional drum system. As will be seen from the photograph of the equipment in *fig. 2*, the documents are simply placed on an endless belt moving at a speed of 30 cm per 8 seconds. They are stuck on to the belt by an electric charge. The documents, consisting of light or dark paper, with drawings, photographs, or hand-written, typed or printed text, are scanned by a rapidly revolving optical system at a certain point in their passage, an additional advantage of this *continuous scanning system* being that the documents need not necessarily be of the standard quarto size, 29.7 cm in length: *any length may be used* provided the width does not exceed approx. *22 cm* [6]).

As already mentioned, the equipment under discussion will transmit an image of 1.5×10^6 picture elements in 8 seconds. This means that the receiver is allowed only 1/200,000 sec. for the exposure of each element. The light-source, the luminous intensity of which must be capable of keeping in step with modulations up to 100 kc/s, is a special gas-discharge lamp which we have developed for the purpose. This lamp, together with a high-speed optical system, makes it possible to obtain the required density (max. 1.5) on *standard positive film* within the short space of time in question. The resolving power of this film is much higher than that of the scanning spot (see table I); the image in the receiver can therefore be recorded greatly reduced in size in comparison with the original, without any loss of definition, and the receiver has therefore been designed to give a reproduction *reduced 6 times in size*. The amount of film required is thus reduced by a factor of 36.

The 45 mm film passes continuously through the receiver, at a certain point in which a rapidly rotating optical system "writes" the lines on the

[6]) This principle of continuous scanning was first employed in 1928 by Alexanderson, but the essential increase in the transmission rate, which in our case was the main reason for adopting this method, could not be satisfactorily achieved with the means available in those days, At that time the avoidance of the necessity for loading the documents onto a drum and the advantage of freedom in regard to document size were regarded as primary factors.

Fig. 2. Transmitter of the Philips high-speed facsimile equipment in operation. Documents of any size up to 22 cm in width are placed on an endless belt running just below the aperture in the table top. When finished with, they fall into the collecting tray seen at the front end of the unit.

film with the requisite intensity of every element. After development and fixing, the documents can be projected full-size while the film is still wet or, if required, one or more copies of each can be made in this way on an inexpensive photostat paper. *Fig. 3* depicts the receiving equipment in use.

In order to complete our review of this equipment it may be said that the receiver is very simply switched over to produce either a positive or a negative image of the original; further, the electrical circuit is such that the average brightness of the original document (the "direct current component" of the image signal) is correctly reproduced at the receiving end. The equipment is capable of transmitting black-and-white pictures or half tones (photographs) as required [7]).

Synchronisation of the revolving optical systems of the transmitter and the receiver is

[7]) The designation "picture telegraphy" is sometimes applied specifically to half-tone transmission and "facsimile transmission" exclusively to black-and-white, but we have not adopted this distinction.

effected by means of synchronising signals, transmitted with the image signal, which control the speed of the driving motor at the receiving end: this feature ensures that the maximum differences in phase occurring in practice between transmitter and receiver are limited to 1/2°, corresponding to a line displacement in the image, in its own direction, of only 0.5 mm. In the event of an interference (as may be caused by fading), the relative phasing corrects itself aperiodically in one second, this being the equivalent writing time of about 200 lines; the resultant displacement among the lines, even in the worst case, is therefore imperceptible.

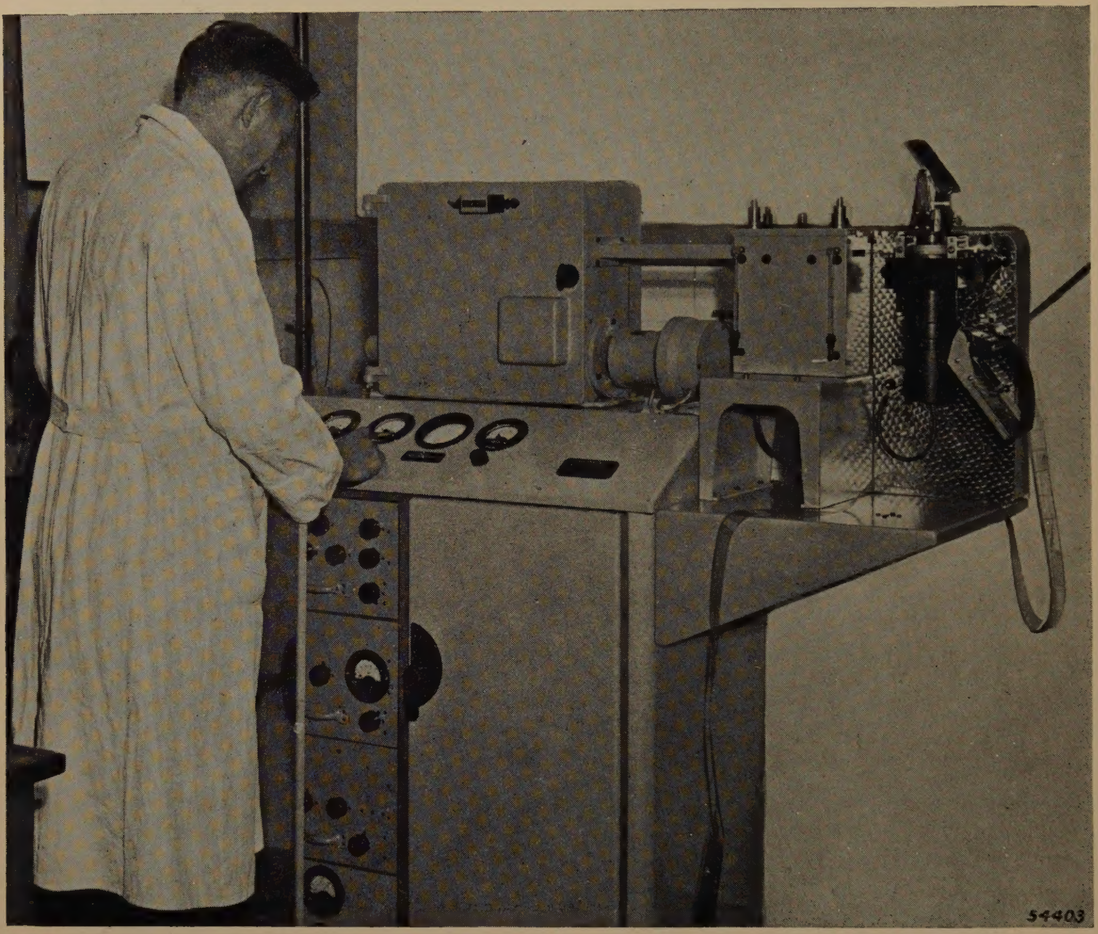


Fig. 3. Receiver for high-speed facsimile transmission. The film on which the images are recorded is seen issuing from the machine on the right.

Possible applications of the new system

Although picture telegraphy as such is, of course, primarily concerned with the transmission of pictures, it is obvious that there are not likely to be many places in the world with such a concentration of pictures to be transmitted that this high-speed facsimile apparatus could be loaded continuously. In connection with its applications, therefore, one of the first possibilities that came to mind is the transmission of illustrated text material. An example where all the advantages of the new system may be utilised to the fullest is to be found in the newspaper business.

It is quite a normal procedure to print and distribute in the provinces identical copies of a large city newspaper, possibly with the inclusion of a local-news page. The text of the more important news is usually transmitted to the appropriate point in the provinces by telephone or teleprinter, so that it will not lose too much of its news value. The ordinary teleprinter service will handle 1000 characters in $2^1/_2$ minutes, which means a period of some three hours for two pages each of 40,000 letters. Then the type has to be set, corrected and laid out before printing can be commenced. Using the new facsimile system, the same two sheets, divided into 8 quarto sheets, can be transmitted in about 1 minute. Re-setting of the type and the subsequent operations are then eliminated, since the reduced reproductions on the film can be

immediately used for making full-size blocks, from which the paper is then printed. The job of making these blocks involves very much less time and labour than the setting of type, whilst line drawings or photographs in the original paper can be reproduced along with the text without any difficulty.

Another use of the system, in which all its essential features can be employed, might be found in the transmission of ordinary letter post between the principal centres of a country. During the night, when carrier-telephony cables are more or less idle, a facsimile unit of the type under review would be able in five hours to transmit a good 2000 quarto-size letters, or proportionately more of a smaller size. In certain cases where identical letters are to be sent to numerous addresses it would mean a great advantage that the contents would have to be transmitted only once, since the receiver supplies a film of the letter (as a negative, if desired) and copies can be made on the spot. Again, the addressees can be furnished with two or more copies of any given letter, as is often required in business correspondence. If a filing system of all incoming items is to be maintained, the fact that a small film of each document received is immediately available may be very useful; microfilm archives of this kind are very widely employed today.

The particular advantages of this system might lead one to infer that it will oust the teleprinter, but this is not very likely, seeing that the latter, being intended for a more limited performance than the facsimile system, is able to perform its allotted task more economically. Let us for a moment look more closely at this question. From the figures given it follows that the teleprinter will transmit a message of roughly 4000 letters, this being the maximum contents of a typed sheet of letter paper, in about 10 minutes — our facsimile equipment does it in 8 seconds. At the speed in question the teleprinter, however, uses a frequency band of only 120 c/s, as compared with 100 kc/s for the facsimile system. Since the use of a cable calculated on the basis of the period of usage as well as on the required frequency band represents by far the greater portion of the operating cost, the teleprinter, despite its slow transmission powers, is more economical than the facsimile by a factor of 10 to 12. The explanation is quite simple. The teleprinter requires 7 impulses for each character transmitted, whilst the facsimile system transmits, per quarto sheet, 1.5×10^6 image elements, or 0.75×10^6 impulses, that is an average of 200 impulses per character. The teleprinter is able to function on such a small number of impulses because it employs both standardisation and code; textual matter is expressed in the form of a small number of standardised letter, figure and other symbols (about 50 in all), each of which is represented by only a small number of impulses (actually 7), spaced out in accordance with a certain code. This code has been given once for all to the receiving stations by means other than the transmission channel and is incorporated in the mechanism of the recording machines.

The facsimile system, on the other hand, transmits every individual peculiarity of the characters and faithfully measures out and reproduces all spaces and blank parts of the sheet. Its use is therefore economically justified only in cases where it is just those peculiarities of form that are important, as in hand-written correspondence, which simultaneously transmits something of the writer's own personality; or, again, where the blank parts are essential features, as in pictorial representations or specially "made up" textual subjects; or finally, in other cases as outlined above, where characteristic advantages of the system, swing the balance in its favour.

A DEMONSTRATION STUDIO FOR SOUND RECORDING AND REPRODUCTION AND FOR SOUND FILM PROJECTION

by the ELECTRO-ACOUSTICS DEPARTMENT. 725.81

At the commencement of 1948 a new demonstration studio was placed at the disposal of the Electro-Acoustics Department of the Philips Factories at Eindhoven. Known as the ELA Studio, it is equipped for demonstrations of various types of programme sources, amplifiers, loudspeakers and film projection equipment, as well as for sound recording by different systems. The acoustic properties of the studio are such that the reverberation time at the higher frequencies (0.9 sec at 2000 c/s) is only slightly less than at the lower frequencies (1.3 sec at 100 c/s), this having a very beneficial effect on the high note response. An elaborate relay system permits of any combination of a sound source (microphone, "Philimil" tape, magnetic tape, or radio receiver), an amplifier, and one or more loudspeakers. From the control desk one or several programmes can be passed to different recording equipment, viz. the Philips-Miller, the magnetic or the photographic equipment, or the gramophone recording unit. Arranged round the studio itself are a microphone room, "speech studio", projection, control and recording rooms.

For the effective demonstration of electro-acoustic equipment such as microphones, pick-ups, amplifiers, loudspeakers and so on, a hall possessing certain acoustic properties — amongst others those relating to reverberation time and sound insulation — is indispensable. This being so, the necessary devices to make rapidly any desired combination of these different apparatus is also essential, the final requirement being a certain degree of comfort in which to judge the results.

Prior to the war, the Electro-Acoustics Department had at their disposal a hall in one of the Philips factories which more or less met the conditions outlined, but this was completely destroyed in 1942.

It was then decided that as soon as the opportunity presented itself, a new hall was to be built and equipped, but with every modern facility and much wider scope; by this is meant that it would have to be suitable for soundfilm projection and for use as a studio for sound recording, for post-synchronisation of films and also for radio transmission.

A studio on these lines, called the ELA Studio (*EL*ectro-*A*coustics) was completed early in 1948. It includes a microphone room, "speech studio" and projection, control and recording rooms. *Fig. 1* gives a good impression of the finished studio arranged for film projection. The main measurements are: length 17.6 m, width 11.6 m, height 7 m (58′ × 38′ × 23′); a plan view of the whole project is given in *fig. 2.*

Before embarking on a technical description, let us say a few words about the architecture and acoustics.

Architecture

In the design of the studio the scope of the architect was in many respects limited. He was obliged to take into account the special conditions to be met in the matter of acoustics (see later paragraph), air-conditioning and heating; moreover, the electrical wiring was to be concealed from view and yet easily accessible at various points, but, notwithstanding all these restrictions a harmonious effect was created.

The lower part of the walls is panelled in dark walnut, and the same material is used for the panels covering the ventilation shafts and for the border of the ceiling. Above the dado the walls are covered with a thin fawncoloured fabric to conceal the sound-absorbing material with which they are lined, the severity of these surfaces being relieved by silk cords stretched over the fabric to form a diamond pattern.

The lighting is partly direct from lamps on the ceiling and partly indirect from cornices running along the top of the wall panelling; the latter lighting therefore mainly illuminates the upper part of the walls.

Acoustic properties

We must here distinguish between the a c o u s t i c s and the s o u n d i n s u l a t i o n of the studio.

Acoustics of the studio

First of all, what are the requirements governing the acoustics, and in particular the reverberation time, of a hall intended to serve both for sound recording and the reproduction of sound by means of loudspeakers?

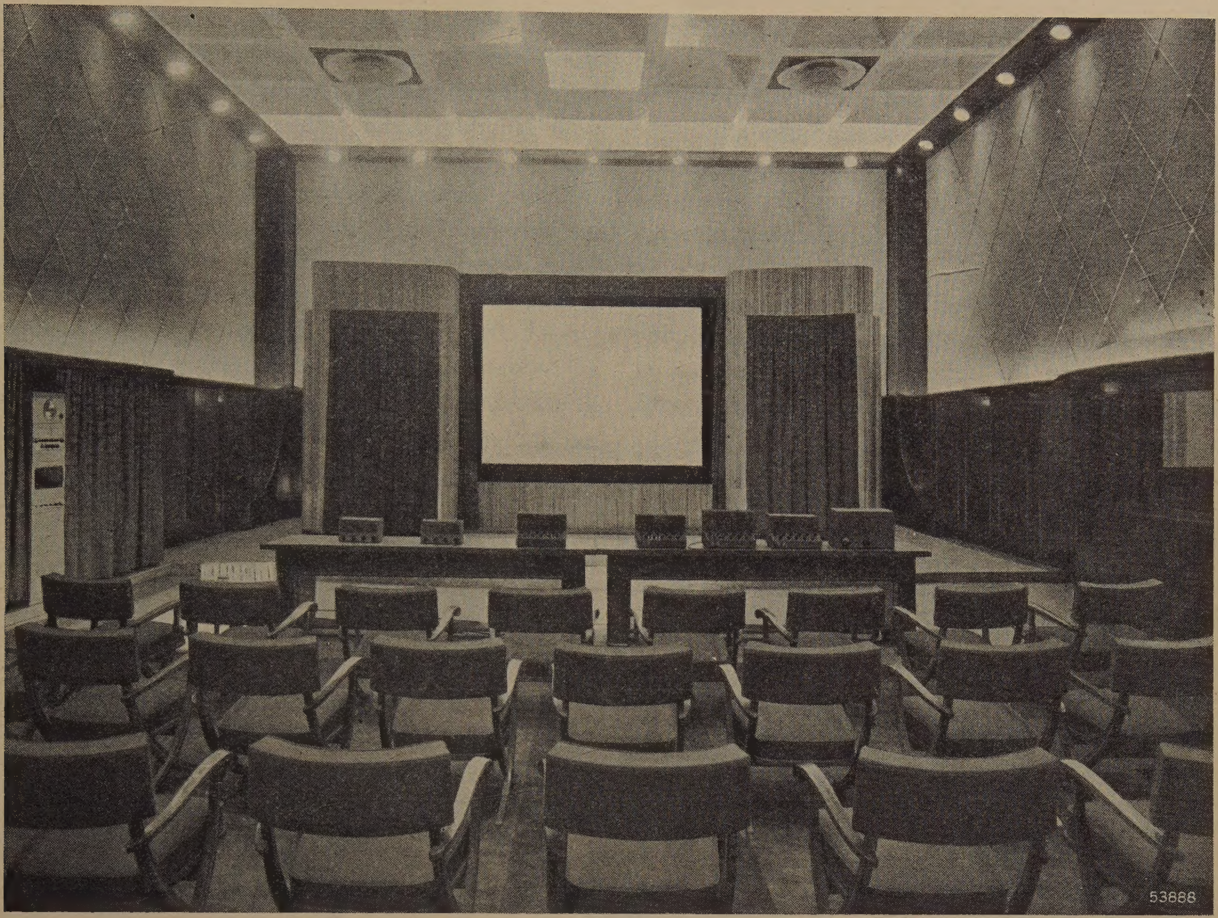


Fig. 1. The ELA Studio, arranged for film projection.

Clearly, the reverberation time must not be too long in either case, as this would mean too much merging of the individual sounds.

On the other hand, a recording studio must not be too "dead" acoustically, for in the extreme case, with no reverberation at all, musicians would find themselves in difficulty as their music would sound unnatural. Again, recordings made in an acoustically dead studio need to be played back in a room of outstanding acoustic properties (a rare occurence) if the music is not to sound too clipped.

A room in which is reproduced should not be too dead either, since the listener then does not really "experience" the reverberation already present in the recording; consequently for the proper reproduction of a recording containing only part of the requisite reverberation the room in which the recording is played requires a definite reverberation time.

In both cases, that is, for the recording of music as well as for its reproduction by means of loudspeakers, the reverberation times are therefore subject to certain limitations and the most suitable of these were found to be:

100 c/s	1.3 sec,
800 c/s	1.0 sec,
2000 c/s and higher	0.9 sec.

To ensure good intelligibility the reverberation time for speech should usually be shorter than for music; generally speaking, large halls are therefore less suitable for recording speech. For this reason a small speech studio and also a microphone room, have been included in the layout of the studio complex, both of these rooms being almost completely dead acoustically.

The reverberation time of a hall of the dimensions in question (1500 cub. m) would be far too long for both high and low frequencies if the walls were of bare brick. Moreover, the absorption of brickwork increases with the frequency; the reverberation time would therefore be longer for the low frequencies than for the high, which would cause the hall to sound "hollow".

It is a characteristic of almost all sound-absorbent material that the absorption increases with the frequency, in other words, when the absorption of the lower frequencies is satisfactory, that of the high frequencies is too great; this cannot be tolerated,

however, since sound depends for its brilliance upon these higher frequencies. In order to attain the reverberation times specified above, steps had to be taken in the construction of the studio to ensure extra absorption of the lower frequencies.

In the calculation of the reverberation time, the following fixed elements had to be taken into account:

1) the ceiling of plaster in the form of partitions (fig. 1) which diffuse the sound; also the wooden border round the ceiling;
2) the wood parquet flooring, partly covered with carpets;
3) those parts of the walls taken up by doors and windows.

Only the remaining parts of the walls were available for applying acoustic materials.

Measurements were duly taken from a large number of building and furnishing materials to determine their respective sound absorption coefficients as a function of the frequency, calculations in respect of various designs being based on these values.

The reverberation times of the ultimate project, as measured at different frequencies [1]) proved to be in complete agreement with the required values.

The wainscoting and the covering of the ventilatings hafts are in the form of wood panelling mounted on sound absorbent material, whilst above the panelling the walls are covered with various kinds

[1]) For the method employed in taking these measurements see W. Tak, The measurement of reverberation, Philips Techn. Rev., **8**, 82-88, 1946; also Measuring reverberation time by the method of exponentially increasing amplification, Philips Techn. Rev., **9**, 371-378, 1947 (No. 12).

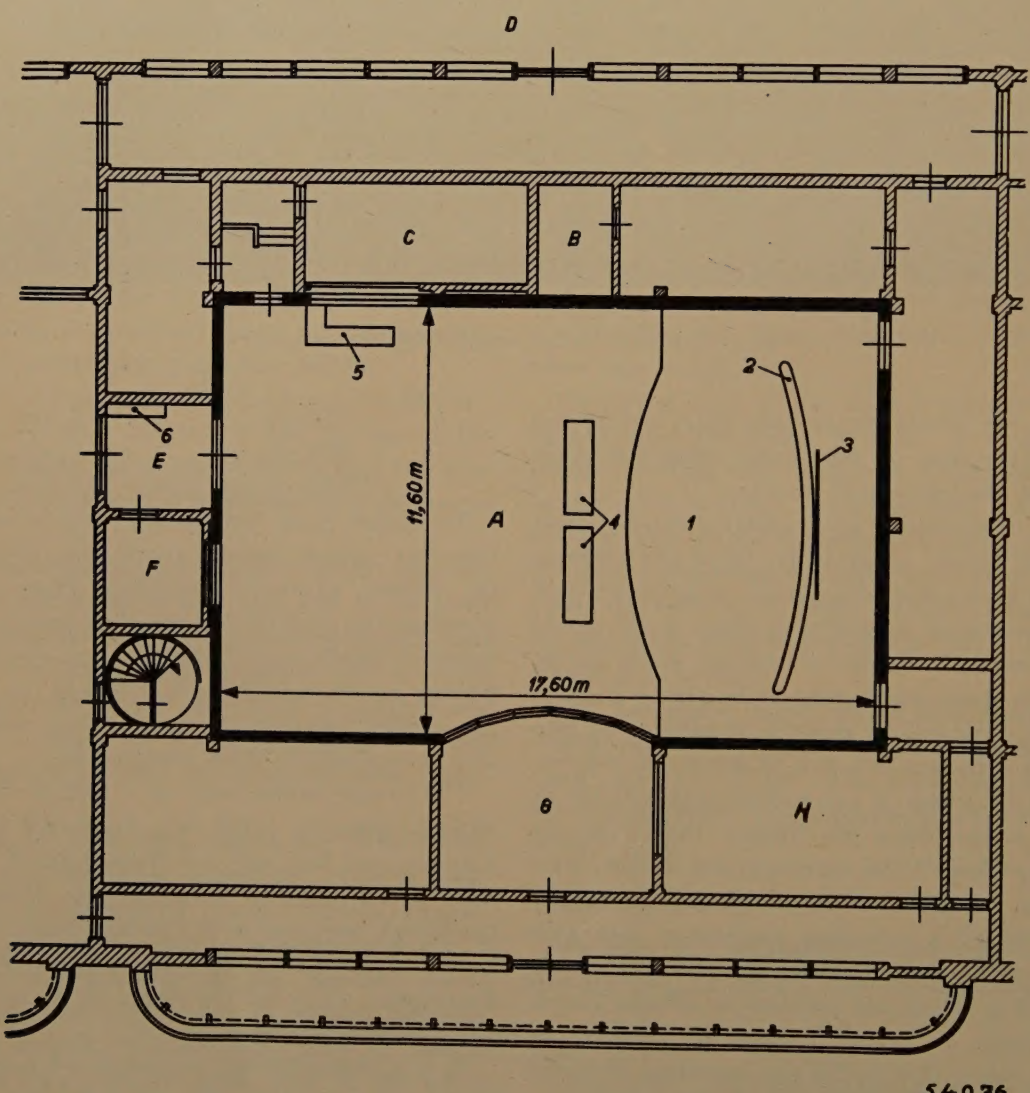


Fig. 2. Plan view of the studio and associated rooms, equipment etc. A = studio with *1* platform, *2* baffle, *3* projection screen, *4* demonstration tables with amplifiers, *5* desk with gramophones, master control panel etc, B = battery room; C = microphone room; D = roof terrace; E = vestibule with equipment for directional radio reception (*6*); F = speech studio; G = control room; H = sound recording room.

of wood fibre-board; both panelling and fibre-board are so constructed and mounted as to effectively solve the problem of ensuring sufficient absorption of the lower frequencies and not too much absorption of the higher ones. For the sake of appearance the fibre-boarding is covered with the thin material alluded to above which has little or no effect on the acoustics.

Sound-insulation

In order to prevent the entry of disturbing noises, the studio — weighing some 400 tons and being situated on the top floor of a building about 40 m (130′) in height — is insulated from the main building by several layers of bituminous material between the floor of the studio and its footings (*fig. 3*).

The ante-rooms are separated from the main studio by cavity walls, and any windows occurring in these walls are of double glass; the construction of the doors and frames is also such as to prevent the entry of any sounds from outside.

Let us now turn to the equipment: in the main this falls into three categories, viz.:
1) Electro-acoustic reproduction equipment;
2) Cinematographic equipment;
3) Sound recording equipment.

Electro-acoustic reproduction equipment

Programme sources

The ELA Studio is provided with the following "programme sources":
1) microphones,
2) gramophones,
3) playback equipment for Philips-Miller recordings,
4) playback equipment for magnetic recordings,
5) various radio receivers,
6) music lines (telephone lines for music transmission).

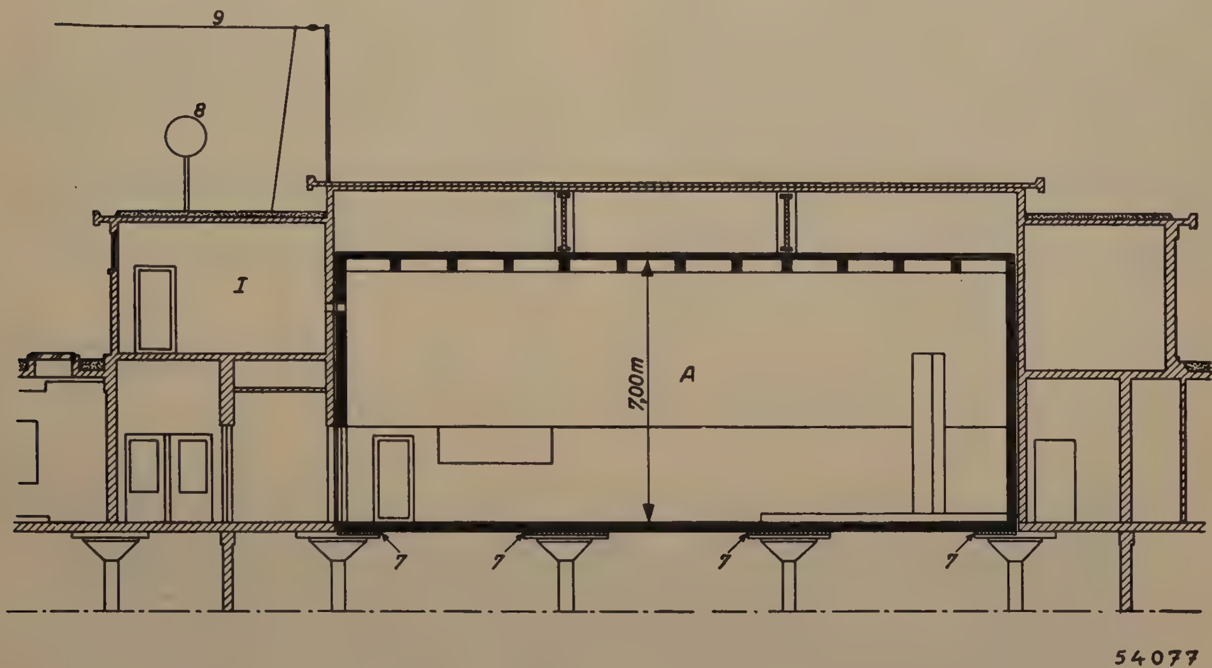


Fig. 3. Cross-section of side elevation. A = studio; I = projection room; 7 = sound-insulation; 8 = loop aerial; 9 = normal aerial.

Microphones of different types are provided in the microphone room (*fig. 4*).

For gramophone music there are three turntables (*fig. 5*), each fitted with three different pick-ups which can be switched into circuit as desired.

Mounted close to these is the Philips-Miller playback equipment and an ordinary radio receiver. A special receiver is also provided (*fig. 6*) for directional reception in cases where it is required to eliminate interference from other stations; this set is served by a loop aerial (fig. 3) which can be employed in conjunction with an ordinary aerial if desired [2]). The bandwidth of this

[2]) P. Cornelius and J. van Slooten, Installations for improved broadcast reception, Philips Techn. Rev. 9, 55-63, 1947 (No. 2).

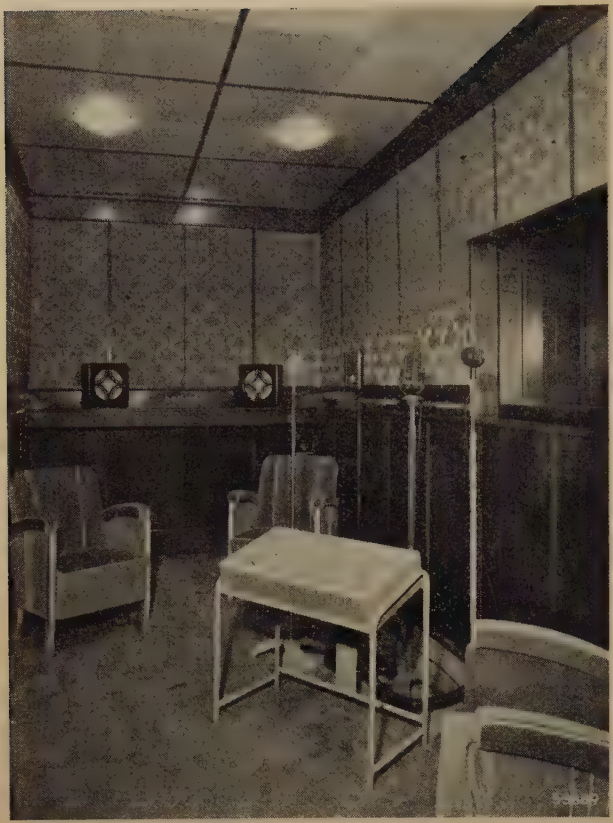


Fig. 4. Microphone room (*C* in fig. 2), with four different types of microphones. In the foreground a movable switch panel with push-buttons and pilot lamps. The two loudspeakers (in background) have been designed for radio relay.

receiver is variable to a greater extent than is the case with ordinary receivers; in fact the directional properties of the aerial system make it possible to receive broadcast transmission without interference at much greater bandwidths than whith conventional types of receivers.

Playback and recording equipment of the magnetic type is installed in the recording room.

Land-lines may for instance provide connection with the Concertgebouw, Amsterdam [3]), the Netherlands broadcasting studios etc.

Amplifiers

For demonstration the amplifiers are located on tables and along the wall in the main studio (*fig. 7*) and can be connected as required between any particular programme source and the loudspeakers by means of a system of relays, to which further reference is made in a following paragraph.

Loudspeakers

A large baffle stands on the platform of the studio (*fig. 8*), offering space for 12 loudspeaker units

[3]) A recent article in this Review contains a description of the experimental „duplication" in the ELA Studio of a performance given in the Concertgebouw; see R. Vermeulen Duplication of Concerts, Philips Techn. Rev. 10, 169-177, 1948 (No. 6).

Fig. 5. Desk (5 in fig. 2) accomodating (from front to rear): Philips-Miller playback equipment, master control panel with push-buttons and pilot lamps, programme level-meters, three gramophones (each with three different pick-ups), radio receiver.

Fig. 6. Rack containing receiver for directional radio reception, monitor speaker, gramophone, programme level-meter and switch panel with correcting filters.

any one or more of which can be connected to each of the different amplifiers. Other speakers, for open-air reproduction, are located on the roof terrace; they can also be linked up with the amplifiers and programme sources mentioned.

The microphone room further provides facilities for listening to loudspeakers intended for use in small rooms or in the home, as for example, with radio-relay.

Stereophony

Needless to say, the studio is also equipped for stereophonic reproduction [4]) of stereophonically recorded sound either by the Philips-Miller or by the magnetic tape system, or as picked up in a remote concert hall by means of a stereophonic microphone unit. In the latter instance the ELA Studio is linked up with the concert hall by land-line (see footnote [3])), or by special radio transmission, employing two transmitters and two receivers.

Switching system

The system of switching is designed to establish rapidly any desired combination of programme source, amplifier and loudspeaker. Each of the sources of music can be connected to the amplifier input cables via relays, and the output of each of the amplifiers is passed through one of a second set of relays to an output line, to which a third group of relays connects one or more of the loudspeakers.

The various relays are operated by means of push-buttons on four parallel-connected control panels, two of which are fixed, namely the master panel in the studio and that on the terrace, whilst the other two are movable, one being in the studio and the other in the microphone room.

Each of these four panels enables a selection to be made from the available programme sources, amplifiers and loudspeakers, and, when the buttons on any one of these panels are depressed, pilot lamps light, not only at the buttons concerned, but also at the corresponding buttons on the other panels and at the particular apparatus put into circuit.

The cabling, which in the case of such a complex system is necessarily extensive, has partly a fairly high and partly a very low power level. In order to avoid the possibility of consequent cross-talk, the ducts containing the cables are divided into four compartments, each one screened from the other and containing groups of lines of roughly the same power level.

Cinematografic equipment

The centre part of the speaker baffle on the platform is folded back sideways when the projection screen (3.65 m $\times$ 2.75 m, or 12′ $\times$ 9′) is to be used. Behind the screen the cinema speakers are mounted, those for the low frequencies on a large wooden horn and those for the high frequencies on a multicellular metal horn.

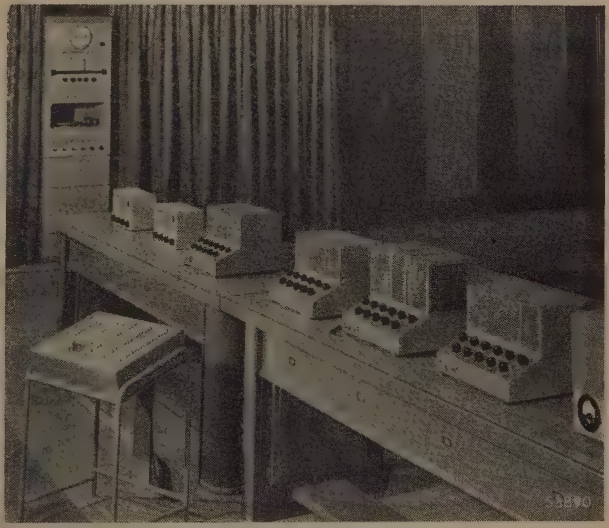


Fig. 7. Tables with demonstration amplifiers (4 in fig. 2). On the left in the foreground is a movable control panel similar to that shown in fig. 4.

[4]) K. de Boer, Stereophonic sound reproduction, Philips Techn. Rev. 5, 107-114, 1940.

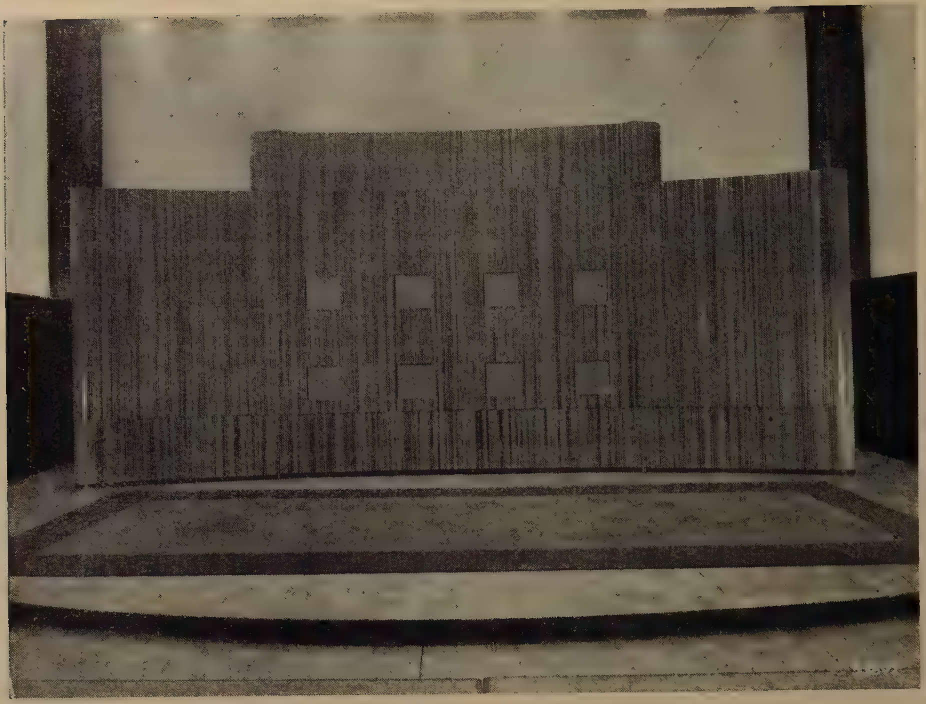


Fig. 8. Baffle on the platform of the studio (*2* in fig. 2) with 8 loudspeaker units (this number can be increased to 12). The centre part folds back sideways to reveal the projection screen (see fig. 1).

In the projection room there are two projectors (*fig. 9*) with the amplifier cabinet in between. Each of the high-intensity arcs is fed from a separate rectifier, housed in an adjoining room.

There is also accommodation for a third projector for demonstration or experimental purposes.

Panels with push-buttons and switches are mounted on the wall beside each of the projectors for controlling the rectifiers and the studio lighting. As regards the latter, this is provided by incandescent lamps (total consumption 20 kW). The dimmer for the studio lighting and the switch for the motor operating the curtain in front of the screen can be controlled from the projection room as well as from the studio itself; the sound volume, too, is controllable from both points.

All possible measures have of course been taken to minimize the risk of fire originating in the projection room; the windows between the latter and the studio are fitted with steel shutters (fig. 9), held open by electro-magnets when a film is being shown; in the event of the film catching fire the energizing current of these magnets is automatically cut off and the shutters drop.

Sound recording equipment

Various installations are available for the recording of sound, which may be derived from any of the following sources:

1) microphones in the main studio,
2) microphones in the speech studio,
3) music lines,
4) other sound sources.

The signals arrive at a four-channel mixing desk in the control room (*fig. 10*), from which a large window gives the operator a wide view of the studio.

Installations for the recording are located in an adjoining room. The four systems employed, which can record a same programme simultaneously, are:

1) Philips-Miller recording equipment,
2) magnetic recorder,
3) photographic sound recording installation,
4) gramophone recording unit.

A short description of each system may not be out of place. In the Philips-Miller system [5]), the sound track is cut electromagnetically in a "Philimil" tape, this being of celluloid with a transparent coating of gelatine, on top of which there is a very thin and opaque layer. The recorded sound can be reproduced during the recording process.

Copies of the "Philimil" recordings may be made either photographically [7]) or mechanically, accor-

[5]) R. Vermeulen, The Philips-Miller system of sound recording, Philips Techn. Rev. **1**, 107-114, 1936.

[6]) See R. J. H. Alink, C. J. Dippel and K. J. Keuning, The metal-diazonium system for photographic reproduction, Philips Techn. Rev. **9**, 289-300, 1947, (No. 10).

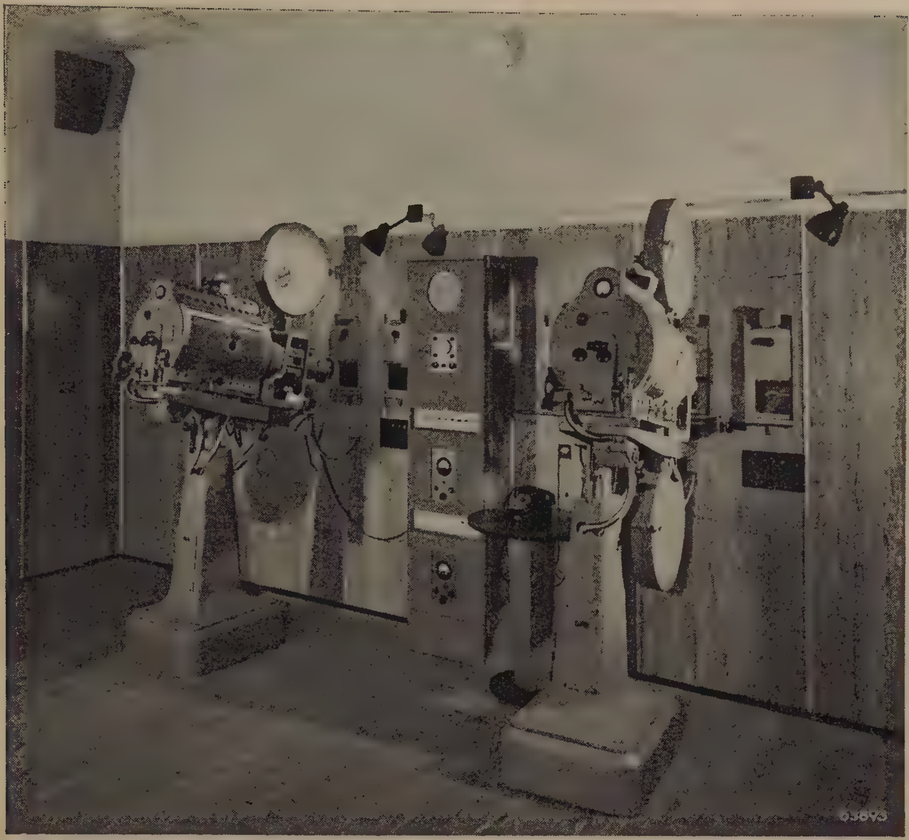


Fig. 9. Projection room, with two Philips Type FP 7 projectors and Type 2834 amplifier cabinet. On the wall, near each projector, the small panels which carry the pilot lamps, push-buttons and switches for changing-over the rectifiers and for controlling the studio lighting. The windows are fitted with automatic steel shutters. A communication speaker is seen in the left hand top corner.

ding to the particular purpose for which they are intended.

For film studio work perforated „Philimil" tape 35 mm in width is used; for broadcasting purposes the tape is only 7 mm wide and unperforated. Both varieties are handled in the recording room; *fig. 11* shows the 7 mm equipment.

With the magnetic system [7]) a sound track of varying remanence is produced in a tape of magnetic material; this also permits of immediate playback.

The latter feature is absent in the photographic system (also mentioned in the article

[7]) This system is employed for professional purposes only.

Fig. 10. Mixing desk in the control room (*G* in fig. 2). The bay-window provides a wide view of the interior of the studio. The window on the right gives on to the recording room.

Fig. 11. Recording room (*H* in fig. 2). Centre: twin Philips-Miller recording equipment for 7 mm tape. Right: amplifier rack. Left: rack with power supply units.

referred to in footnote [5]), as in this case the sound track requires development and printing before playback is possible.

Gramophone records are normally cut on equipment adapted for the recording of sound on shellac discs; special apparatus is provided in the studio for the making of records on wax discs.

Another application of sound recording is the post-synchronisation of film-sound, facilities for which are also included in the studio equipment. The silent film is projected on the screen, the appropriate sound being produced either in the main studio or in the speech studio, and recorded on "Philimil" tape, or by the photographic process.

Intercommunication system

To establish communication between the studio and the ante-rooms, three different systems are in use, each of which has its own merits. These are:

1) house telephone,
2) a system of light signals,
3) microphones and loudspeakers.

With this we close our description, although many details have not been touched upon; it is intended only to give a general impression of the extensive electro-acoustic and cinematographic facilities with which this up-to-date studio has been equipped.

CERAMICS AND THEIR MANUFACTURE

by R. A. IJDENS.

666.3: 621.315.612

The art of producing utensils and art wares from ceramic materials has been practised for centuries, but it is only since the end of the last century that these materials have been adapted for use in the electrical industry in the form of insulators and dielectrics for capacitors. The requirements imposed in the field of high-frequency equipment as regards the dielectric constant, dielectric losses, the coefficient of expansion and mechanical properties have greatly accelerated the development of this branch of the ceramic art and in this development Philips Laboratories at Eindhoven have played an important part. The aim of this article is to present a brief survey of the different methods employed in a factory in the preparation of ceramic materials; of the different ceramic compositions manufactured at Eindhoven at the present time and of the different purposes for which they are used. Reference is also made to the phase diagram of the system MgO-Al_2O_3-SiO_2, in order to illustrate the manner in which the characteristics of the final product are related to the composition of the ceramic mixtures.

Development of the ceramic art

The ceramic art as based on the manufacture of objects from inorganic materials dates back to antiquity: many centuries before the christian era it formed part of the culture of those days. The word "ceramic" is of Greek origin; in Hellas the potter was known as "kerameus" and the word "keramos" designated the plastic raw material employed by him.

A characteristic feature of the process is that the raw materials are mixed with a liquid (usually water) to a plastic dough before they are moulded into objects of the desired form, being subsequently fired at a high temperature to produce the necessary strength.

In principle, the manufacture of ceramic articles has changed very little in the course of time; it has merely undergone refinements and improvement and, with the growth of industry in general, has been adapted to mass production methods.

The selection and use of the most suitable raw materials for ceramics has always been a most important question; in fact it is not always easy tor ecognise exactly the right material, since chemical analysis and X-ray examination reveal but very little about the practical results that may be anticipated. These raw materials have always been of mineral origin, the most important being clay, which gives the ceramic mixture the required plastic consistency.

When electricity began to play such an important part towards the end of the last century, it was only a matter of time that a large demand for ceramic articles was developed by the electrical industry; insulators were needed for many different purposes and porcelain was quickly recognised as an excellent insulating material. Very soon all kinds of electrical components were being produced in porcelain or in some cases in steatite; these materials were, at any rate in the beginning, based on more or less classical compositions.

The development of the high-frequency technique, however, brought many changes in its train, for the well-known varieties of steatite and porcelain proved to be unsuitable for this purpose and new grades had to be developed; often it was to introduce new types of raw materials, to meet the demands of the electrical experts for more and more ceramics of widely divergent properties.

Ceramic materials for high frequencies

The fact that the earlier grades of porcelain and steatite were not suitable for high-frequency work must be attributed to their high dielectric losses under these conditions. It is a well-known property of an insulator that, when placed in an electric alternating field, it consumes part of the electrical energy and converts it into heat. Provided the heat thus developed corresponds only to a small proportion of the total amount of energy in the field, it can be represented approximately by the expression:

$$W = V^2 \,.\, 2\pi f \,.\, C \,.\, \tan\delta, \quad . \; . \; . \; . \quad (1)$$

where V = the high-frequency voltage (r.m.s. value),
f = frequency,
C = capacitance,
δ = loss angle of the material.

The value of the capacitance depends upon two factors, namely the dielectric constant ε and a form-constant K, determined by the shape of the

insulator. Expression (1) can therefore also be written:

$$W = (V^2 \cdot 2\pi f \cdot K) \cdot \varepsilon \tan\delta \quad . \quad . \quad . \quad (2)$$

In a given device or technical application, V, f, and usually also K are known in advance: ε and $\tan\delta$ are thus the only factors available for modification to ensure that the ceramic product will meet the particular demands with respect to the dielectric losses.

In principle, both ε and $\tan\delta$ are moreover dependent on the frequency. In the range of radio frequencies, however, ε may be regarded for all practical purposes as being independent of the frequency and, for most materials, $\tan\delta$ does not vary with the frequency to any great extent either, in this range. This means that, in view of expression (2), the dielectric losses of most materials, broadly speaking, increase in proportion to the frequency; thus, if it is required to limit the dielectric losses in electrical equipment or circuits working at high frequencies, the product $\varepsilon \tan\delta$ (the loss factor) must be kept as low as possible. In all cases where ceramics are employed in the construction of insulators (e.g. supports for high-frequency lines) every effort is therefore made to ensure low values of ε and $\tan\delta$.

In capacitors, however, it is usually desirable to aim at high values of ε with a view to restricting the physical dimensions of the capacitor itself, and here it is all the more important that $\tan\delta$ should be as low as possible: the first material to come into consideration for this purpose is titanium dioxide, the dielectric constant ε of which, in case of the pure material, is 115. At the same time, it is a drawback of this material in many of its applications that ε has a high negative temperature coefficient, viz. -8×10^{-4} per °C, which tends to produce variations in the tuning of an oscillatory circuit some time after the current has been switched on. If this is regarded as an obstacle, some other kind of dielectric must be employed, the dielectric constant of which has a very low temperature coefficient, and a lower value of ε may then have to be accepted. Mg_2TiO_4 and other oxide mixtures come into consideration for this purpose.

When capacitors of very small physical proportions are required, having much higher capacitance values than those under review, use may be made of certain titanates ($BaTiO_3$, $SrTiO_3$): in the Philips Laboratories, for example, two such titanates have been developed, of which $\varepsilon = 1200$ and 2500. The temperature coefficients of the dielectric constant of these materials vary considerably according to the range of temperatures concerned and, wherever their use is favoured, the higher loss factor must be accepted as inevitable.

The choice of ceramics for use as constructional material is quite frequently governed by the high stability of thier physical form and chemical composition. In the first place consideration must be given to the coefficient of expansion of the material to be used, for it is quite possible that the tuning of an oscillatory circuit may be upset as a result of the slightest expansion or contraction of certain components in the circuit, due to variations in temperature; if this is to be avoided, the use of materials having a low coefficient of expansion is indicated and, in some cases, this may be so important that the question of a low loss factor takes second place. In the following paragraphs it will be shown that such ceramics, having a low coefficient of expansion, can be produced from the three constituents MgO, Al_2O_3 and SiO_2. For the coefficients of expansion of some of the ceramics in common use see *table I*.

Table I. Coefficient of expansion of some of the more common ceramic materials.

Cordierite mixtures	1- 2 $\times 10^{-6}$ per °C.
Porcelain	3- 4
Steatite-porcelain	6- 7
Steatite	8- 9
MgO compounds	10-12

There is a very large outlet for ceramics in the manufacture of electronic valves, in the form of both supporting and insulating elements, and *fig. 1* shows a typical example. When intended for capacitors, or as insulating material to be used in the air, ceramics are needed which have been sintered to the point of impermeability, but for use under vacuum finely porous types are also quite suitable; the degree of importance attached to the insulating qualities of the material within the electronic valve depends upon how low the dielectric losses have to be, and it is a point in its favour that the porous structure seems to have the effect of reducing the dielectric constant in comparison with that of the denser materials of the same chemical composition.

Originally, ceramics for electro-technical purposes were supplied by makers of domestic and art wares, but today the development has in many instances been taken over and progressed by the electrical industries to meet the demand for the many different varieties of ceramics needed to keep pace with the increased scope of high-frequency techniques. This has taken place in the Netherlands amongst

other countries and, in recent years, numerous ceramic materials have been developed in the Philips Laboratories; manufacture was commenced on a regular scale just prior to the last world war [1]).

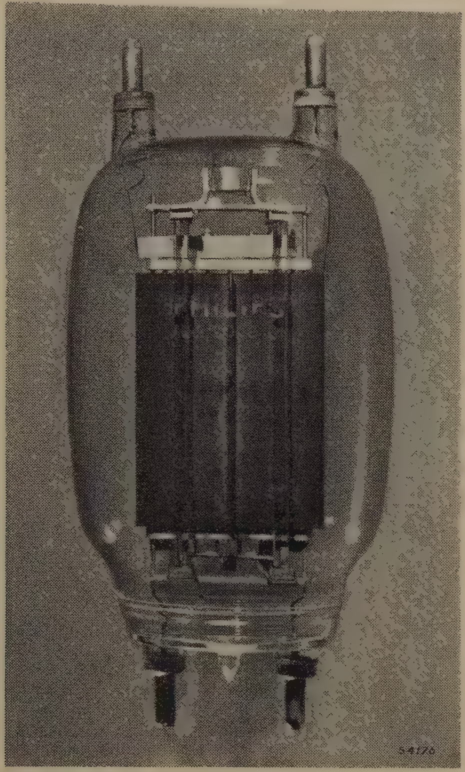


Fig. 1. A transmitting valve (type TB 3/2000) in which ceramic material is used for supports; the electrode system is fixed between ceramic rings.

We shall commence with a brief survey of the methods employed in the manufacture of ceramics and proceed to a discussion of various specific products used for insulation purposes, particularly in the sphere of high frequencies. It will be clear from the remarks that follow that the properties of the final product depend to a large extent on the raw materials used.

A review of titanium dioxide and allied substances for use as dielectric in capacitors, as well as the general uses of titanates, is reserved for publication in two following articles.

[1]) This article is devoted mainly to a discussion on ceramic insulating materials and dielectrics. Apart form these, two other groups of material have been developed by the Physical Laboratories, Eindhoven, namely ceramic resistance materials (semi-conductors) and ferro-magnetic substances for the cores of coils ("Ferroxcube"). These materials, which have found an extensive field of application, have already been desribed in an earlier issue of this Review by E. J. W. Verwey, P. W. Haayman and F. C. Romeyn, Semi-conductors with large negative temperature coefficient of resistance, Philips Techn. Rev. **9**, 239-248, 1947 (No. 8); J. L. Snoek, Non-metallic magnetic material for high frequencies, Philips Techn. Rev. **8**, 353-360, 1946.

Method of manufacture of ceramic products

The finished ceramic product may be regarded as having passed through five distinct phases of manufacture, viz.:
1) preparation of the ceramic mixture,
2) moulding,
3) drying,
4) firing,
5) finishing.

Preparation of the ceramic mixture

The raw materials may be divided into two categories:

The first group comprises the non-plastic constituents, usually present in large proportions in every ceramic mixture and having a major influence on the characteristics of the final product; typical examples of these materials are quartz, feldspar, steatite, magnesite, aluminium oxide and titanium oxide.

The second group comprises the plasticisers and these can be further classified as organic and inorganic; among the latter are kaolin, clay and bentonite, which form a plastic mass when mixed with water. After the firing these materials are still present in the ceramic mass, although chemically changed, and their influence is thus reflected in the final product, this being in certain cases a very desirable characteristic.

The organic plasticisers, which are usually referred to as binding agents or binders, may be electrocol (a farinaceous product), nitro-cellulose, tragacanth, etc. and these are added only in small quantities; once their function has been fulfilled during the moulding process, they are almost wholly burnt away in the subsequent firing operation. The properties of the resultant ceramics are thus governed entirely by the non-plastic ingredients. Organic binders are frequently necessary because inorganic plasticisers such as clay may impart to the final product qualities which tend to conflict with those required.

The raw materials of mineral origin are usually first broken up in mills of the crushing or edge-runner type, after which they are pulverised in a ball-mill. Sometimes — and this refers particularly to kaolin and clay — they are subjected to a precipitation process, being first brought into suspension and then allowed to settle. The raw materials are usually weighed dry to obtain a certain composition, after which they are milled wet in a base-mill. The slip is pumped to a filter press, passing through an electro-manget to remove any particles of iron present in it; the surplus water is removed in

the filter press through filter cloths at a pressure of some 6 to 8 atm. The paste is thus deposited on the cloths in the form of semi-solid slabs 2 to 3 cm in thickness and when these are sufficiently dry they are ground to a powder or to small granules according to the ultimate use to be made of the material.

If no clay or kaolin has already been added to the mixture as plasticiser, one of the inorganic binders previously mentioned is then mixed with the powder to form a plastic mass.

Fig. 2. De-airing pug-mill in operation.

The latter is next loaded into a de-airing pug-mill (*fig. 2*) for removal of all the air occluded during the preceding operations; if this were not done the final product would contain pores, cavities or even channels.

This preparatory processing is rather involved and occupies a considerable amount of time, but it is necessary to ensure complete homogeneity of the material before moulding is commenced.

Moulding

Any one of three different moulding processes may be employed.

In the first of these the powdered material, as it stands, or mixed either with a certain percentage of paraffin wax or a small amount of liquid (water, oil or kerosene), is moulded in dies. Most of the smaller ceramic articles employed for H.F. purposes are moulded in this way, in automatic or semi-automatic presses. We speak of dry moulding when the powder is used without the addition of a liquid, or when only paraffin wax has been added, but when the porcelain powder is admixed with water, kerosene and fat oil a pressing powder is obtained the plasticity of which is higher than that of the perfectly dry powder. By this "semi-wet" moulding method objects of rather more complex form may be shaped; objects with holes in horizontal directions, or those having thin vertical ridges, are therefore moulded in the semi-wet state for preference.

In the second method sufficient water is added to the mixture to produce a perfectly plastic mass suitable for moulding by the extrusion method or by rotary shaping (jollying).

To extrude a tube, a roll of the de-aired material is loaded into a cylinder on the underside of which a nozzle or die, with pin, are fitted, after the manner depicted in *fig. 3;* the respective sizes of the die and pin determine the outside and inside diameters of the ceramic tube thus produced.

For the rotary method a revolving disc, driven electrically or mechanically, is used, the plastic material being shaped by hand, just as on the potter's wheel of old, or special plaster moulds may be used for the purpose; this method is still used in the manufacture of many electrical components such as insulators for high or low tension.

The third moulding method involves the use of the ceramic powder suspended in so much liquid that the mixture is quite fluid, the products being moulded by casting in plaster moulds; owing to its high porosity the plaster absorbs the water, leaving a rigid layer of the material on the walls of the mould, and as soon as the required thickness has been obtained the surplus mixture is decanted. Upon drying, the ceramic moulding shrinks to such an extent that it comes away from the mould and can be easily removed; the plaster mould is then dried for further use.

Finally, it may be mentioned that dry-moulded or "biscuit" fired porcelain, which is ceramic material that has been fired half-hard, can quite well be turned on a lathe.

Firing

When ceramic articles have been moulded into the required shape they are first dried and then fired in a kiln at a temperature that will produce a sintering of the material. By sintering is meant the transition of the mixture from a powder to a coherent solid (which may or may not be porous), the temperature being raised to a level which is not far below the melting point. (If T_s be the melting point in degrees Kelvin, the material is heated to a point between at least $^2/_3\ T_s$ and T_s.) At this temperaure diffusion between the individual particles is accelerated and chemical reactions take

Fig. 3. Extrusion of ceramic tubes. A roll of de-aired raw material is placed in a cylinder, to the lower end of which a die and pin are attached. The inside and outside diameters of the tube are determined by the sizes of pin and die used.

place more quickly; sometimes this involves a change in the crystals to other modifications, whilst in other cases crystal growth may be promoted or entirely new compounds formed.

In the manufacture of some types of ceramics with which we are concerned in the following paragraphs it is essential that firing be carried out to the point where the material actually commences to melt; in this way we ensure that after the firing the crystals are embedded in a glassy matrix.

The ceramic objects are loaded into the kiln in "saggers" (*fig. 4*), to prevent foreign matter from the combustion gases settling on them, and the fully charged kiln is sealed up with brick before firing is commenced. *Fig. 5* depicts a charged kiln after firing has been completed. It takes some days to bring the temperature of the kiln to the required level, depending on the size of the charge.

Two kinds of kiln are in use, namely annular and tunnel furnaces, the first of these being charged and fired periodically. The tunnel kiln has the advantage that it works continuously, with less loss of heat. The articles to be fired are loaded onto trucks and these are drawn through the "tunnel" in regular succession, each truck therefore passing through exactly the same temperature cycle. Such kilns are usually fired by coal gas or producer gas.

The temperature is controlled by means of Seger cones, the material of the latter being such that they soften and curl over, or melt when the temperature of the kiln reaches a certain point. It is also possible to measure the temperature by different kinds of pyrometers (of the thermo-electric or optical type). In comparison with thermo-elements, Seger cones have the advantage that the measurement actually refers to $\int T dt$ (where T is the temperature as a function of the time); they therefore give a better indication of the effect of the heat upon the material in the kiln.

During firing, the material shrinks appreciably, sometimes as much as 30%; the actual amount of shrinkage depends on the composition of the mixture and the method employed in the moulding. As far as dimensions are concerned ceramic articles must therefore be designed with very definite tolerances.

Finishing

After firing and subsequent slow cooling, it may be necessary for the articles to undergo certain

Fig. 4. One type of sagger used for loading ceramic articles into the kiln; it prevents soiling of the articles by the combustion gases.

finishing operations. In some cases they have to be ground, and this can be done by the centreless, circular or horizontal methods. *Fig. 6* illustrates a centreless grinder on which rods and tubes are being trued up, whilst *fig. 7* shows a method of grinding ceramic discs flat and parallel. The finishing or "drilling out" of holes can be carried out only with diamond-tipped tools. Frequently it is necessary to metallise ceramic articles, i.e. to apply a thin film of metal to them, as in the case of capacitor parts, whilst for other purposes it may be found desirable to glaze the surfaces of the material, which, owing to their natural dull finish,

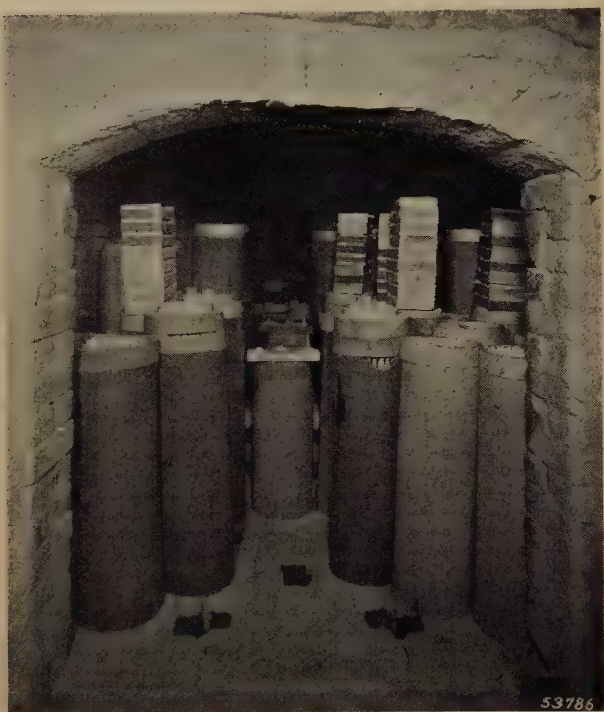


Fig. 5. Kiln charged with fired ceramics. Before firing is commenced the kiln is sealed with brick. The fact that this photograph was taken after firing is borne out by the fact that the Seger cones have melted.

would otherwise very quickly; become soiled. A thin layer of glaze is then applied, after which the article is heated for a little while in a furnace.

Some ceramic mixtures and products

The more important ceramic mixtures used in the manufacture of electrical components, a brief survey of which will now be given, all belong to the ternary system MgO-Al_2O_3-SiO_2, as represented in the phase diagram in *fig. 8* [2]). The names shown in the different phases indicate the crystalline structures produced in those zones upon cooling mixtures

Fig. 6. Grinding ceramic rods and bars on a centreless grinder.

of the different compositions given, and, since sintering entails a commencement of the molten stage, it may be expected that the crystals concerned will be met with in the ceramic material.

Those mixtures which correspond to zone *A* in fig. 8 [3]) are of great importance. They are porcelains built up on a basis of steatite, that is to say the latter substance ($3MgO.4SiO_2$. 1 to 2 H_2O) is employed as primary ingredient; to this is added a sintering agent, mostly clay (aluminium hydrosilicate), sometimes with additions of barium carbonate and potash feldspar ($K_2O.Al_2O_3.6SiO_2$, in which the K_2O may be partly replaced by Na_2O).

The fired material is mechanically strong and dense and consists of enstatite crystals ($MgO.SiO_2$) surrounded by a glassy matrix [4]).

Fig. 7. Grinding machine as used for finishing ceramic discs. These are ground between two flat plates until they are themselves quite flat and parallel.

[2]) Constructed by G. A, Rankin and H. E. Mervin; Amer. J. Sci. **45**, 301-325, 1918, and improved by J. W. Greig, ibid, **13**, 1-44, 1927.

[3]) This Philips product is made under the trade name of "Kersima".

[4]) The conditions governing this phase have been discussed in detail in an article by J. M. Stevels, The vitreous state, Ph. Techn. Rev. **8**, 231-237, 1946.

One of the conditions essential for high mechanical strength of the porcelain is that the crysstalline phase shall be as extensive as possible, and the structure fine-grained. On the other hand, the vitreous phase must not be overlooked, since the composition in the latter state has a very decided effect on the resistance of the final product to temperature variations.

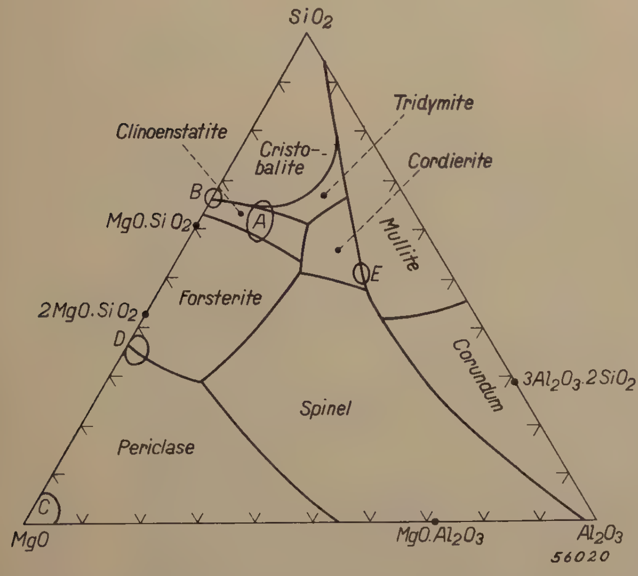


Fig. 8. Phase diagram of the ternary system MgO-Al_2O_3-SiO_2. The names in the various zones indicate the crystalline form produced in these zones upon cooling a molten mixture of the given compositions. The letters *A*, *B*, *C* and *D* indicate the points where the more important compositions occur in the preparation of ceramic mixture as discussed in this article.

The quality of the surface of the porcelain, which may be either smooth and "soft", or rough and stone-like, is governed mainly by the crystal size in the fired product, whilst on the other hand the chemical composition of the material is a criterion for the dielectric properties, and in this connection MgO (and also BaO, which is sometimes added) has a beneficial effect, as it assists in reducing dielectric losses; Al_2O_3 is neutral, whereas SiO_2 and alkalies have the opposite effect. Ultimately, the mechanical strength of the final product will depend very largely on the origin of the steatite used, for there are grades of this material with which, although chemically pure, there is little to be achieved, despite the admixture of sintering agents and other media that may appear necessary. Again, apart from the origin of the raw material, the firing curve is of great inportance: if the material is fired too high, products are obtained in which the crystals have grown too much, resulting in a material of poor mechanical properties; at too low a temperature the fired product will be porous.

Incidentally, those mechanical and dielectric properties which are desired in the final product are not the only factors that decide the composition of the batch. In practice an important question is whether a given mixture will lend itself to easy firing or not; for example it is a great advantage from the aspect of manufacture if the true sintering range — representing the difference in temperature between the beginning of "fusing" and actual "melting" — at a temperature of, say 1370 °C, is 20 degrees instead of only 10.

According to their composition, the substances occurring in zone *A* in the diagram show dielectric losses varying between $\tan\delta = 4 \times 10^{-4}$ and 25×10^{-4} (at 1500 kc/s). In judging the suitability of the material for constructional purposes, the modulus of rupture will also be found an important property, and this should be 1200-2000 kg/cm³. The ceramics in question are employed for capacitors and components working continuously at high frequencies.

A second group of ceramics corresponds to the composition represented by *B* in the diagram, fig. 8 [5]), these being also on a steatite basis. They differ from those mentioned above in that they are dense, but porous, and they are widely used for insulation and constructional purposes in electronic valves (spacers).

The most commonly used composition in this *B*-zone is modified by the addition of barytes and sand to yield a coefficient of expansion such that the material can be employed for sealing to normal soft glass; the mechanical properties are fair, and the modulus of rupture is about 700 kg/cm³. Measured in vacuo, at room temperature, $\tan\delta$ is in the neighbourhood of 10×10^{-4} (at 1500 kc/s) and even at higher temperatures (provided less than 1000 °C) the loss factor, owing to the addition of the above-mentioned substances, is less than that of most of the better known insulating materials.

Of these ceramics in the *B* region, other outstanding features are that the fired product can be machined and that the skrinkage during the firing operation is only small; owing to this latter characteristic many mouldings can be made to very much finer tolerances than in the case of materials in zone *A*. *Fig. 9* illustrates a number of the articles made as part of the normal mass production of the Ceramics Factory at Eindhoven, using the materials with which this paragraph is concerned.

[5]) These materials are known under the trade name "Kerpora".

In the zones marked *C* and *D* in fig. 8 two other interesting materials occur, that is, interesting from the point of view of the coefficient of expansion, which is fairly high for the different mixtures in these groups, namely 10 to 12×10^{-6}. These mixtures are built up from a basis of MgO [6]) and this explains why they are so difficult to process, seeing that magnesium oxide reacts with water in very much the same way as unslaked lime. The addition to these substances of organic solvents or binders further involves a number of technical difficulties. ($2MgO.SiO_2$). Here the objections mentioned above are not so pronounced (difficulty in preparation and selection of suitable sintering agents). By prefiring the MgO with the requisite quantity of steatite it is not possible entirely to suppress the reaction of MgO with water, but it can certainly be greatly reduced, whilst the sintering process is thereby also facilitated, since the melting point of forsterite is not higher than 1880 °C.

Compositions occurring in zones *C* and *D* are eminently suitable for the manufacture of bodies

Fig. 9. Examples of ceramic components for electrical purposes, as produced by normal mass production methods in the Ceramics factory at Eindhoven. These articles are manufactured from materials known under the trade names "Kersima" and "Kerpora".

The first mixtures to be made in this range (*C*) consisted almost entirely of magnesium oxide. Now the melting point of MgO is extremely high, viz. 2800 °C, so that when it was required to manufacture, for special purposes, a closely sintered material at the conventional firing temperature (< 1400 °C) it was found necessary to add a sintering agent; the latter had to be chosen with care, however, in order not to change the coefficient of expansion out of all proportion.

Another group (zone *D*), which was developed at a later date, more nearly resembles forsterite

[6]) The trade name of these materials is "Kermanox".

for wire-wound resistors. Special development in this direction has ensured that the coefficients of expansion of both the wire and the body in which it is wound do not differ to any great extent. When the resistors are fired in the enamelling process, therefore, the turns do not get loose and there is no risk of short-circuiting.

In zone *E* in the diagram we have mixtures of a composition similar to that of the mineral cordierite ($2MgO.2Al_2O_3.5SiO_2$), known for its low coefficient of expansion, which, according to various investigators, is 1.2-2.0 $\times 10^{-6}$. If it were actually possible to produce ceramics of this composition very low coefficients of expansion might be

expected, but in practice this is very difficult, since there is no sintering range; the material either remains porous or melts completely. However, by carefully selecting the raw materials (sillimanite, steatite, feldspar, clay and kaolin) and accepting a slightly higher coefficient of expansion, it is possible to obtain a sufficiently dense material (porosity $\leqslant 2\%$), although the mechanical properties are only fair (modulus of rupture 750 cm³). Owing to its very slight expansion with increases in temperature (coeff. exp. $\leqslant 2 \times 10^{-6}$), this material is very well adapted for coil formers and the construction of oscillatory circuits where variations in capacitance are to be kept as small as possible.

BASIC PRINCIPLES FOR THE FORMULATION OF ILLUMINATION STANDARDS

by A. A. KRUITHOF and A. M. KRUITHOF. 535.241.46:535.736

Utilising the experiments of H. C. Weston, the authors have compiled a table relating to visual tasks as characterised by contrast and visual angle of the details to be observed, from which table it is possible to ascertain the illumination level necessary to guarantee a certain degree of visual performance. The table is based (in so far as visual efficiency is concerned) upon the "relative performance" as defined by Weston. The values of the relative performance given may be employed in place of the more usual qualifications such as "adequate", "good" and so on. Having regard to economic, technical and possibly other points of view, this table is useful in cases where it is required to lay down standards with respect to practical illumination levels.

Physiological aspect and economics of the problem

In the designing of a lighting system it is necessary on the one hand to know something of the manner in which the visual function is influenced by the character of the lighting, i.e., the light distribution, colour, degree of glare, if any, and so on. On the other hand, the most satisfactory illumination level for the task in hand has also to be found. This latter problem, which amounts to the establishing of standards relating to the most suitable illumination level, is the subject of our article.

The considerations upon which such standards must be based are partly physiological in character and partly questions of an economical (and technical) nature: the former factor involves the establishment of a scale of qualification for the illumination levels. In the simplest possible language it is a question of levels of illumination to be attributed to such qualifications as "very good", "good", "sufficient" and so forth, solely from the aspect of the ability to see. In this article this physiological element only will be considered. The economics of the problem do not come into consideration till the question is raised whether in a given instance e.g. for a particular country the standard should be "very good", "good" or "sufficient" when paying attention, among other factors, to local electricity tariffs. (Of course "Inadequate" levels need not be taken into account.) As far as this economical side of the question is concerned, different authorities on the subject appear to hold views are are diametrically opposed to each other, but the simplest answer is surely that wealthy nations (or individuals) are able to afford very good, and therefore expensive, lighting whilst the poorer nations have to be content with something less. On the other hand it is often pointed out that poorer countries cannot afford to bear losses in the processes of production and are therefore obliged to apply the best possible illumination, whereas the affluent may be less careful. These points are mentioned not so much with a view to entering into a discussion of them as to demonstrate the fact that the applications of the physiological principles (the scale of qualifications) constitute a subject in themselves.

The visual task and its performance

It is proposed to term an illumination level "good" when the visual task to be carried out at that level is easily performed.

Although we are still very far from our ultimate objective in making this general statement, it does immediately indicate the course to be followed. The qualification of a given illumination level will depend on the visual task to be performed. In order, then, that the scale of values shall be applicable to every conceivable task and also to make comparison possible with the scales which have already been prepared by numerous other workers in this field, it is necessary to decide upon a measure of the difficulty of a task. Furthermore, the yardstick for the rating will be the ease of its performance and here, too, a quantitative measure is required. Experiments will therefore have to determine the effect of a given level of illumination on this "ease of performance", in relation to different tasks. Finally the scale of qualifications is to be established.

Examples of varying visual rasks are: reading a book, drawing, reading measuring instruments, operating a calculating machine, sewing, or crude or fine assembly work in factories, If we are to express the element of difficulty in such tasks in the form of figures, it must be characterised by means of certain factors which have to be capable of measurement. Such factors might be the following:

1) The size of the detail to be distinghuished,

which is evaluated by measuring the visual angle: a subtended angle of 1′ (one minute of arc) corresponds to 0.1 mm as seen at a range of 30 cm, and it is useful to grade certain common detail sizes in stages, as in *table I.*

Table I. Size of detail to be perceived in different grades of work.

Type of work	Size of detail d	
	Limits	Average
Coarse	> 4.5′	approx. 6′
Normal	2.2′ - 4.5′	approx. 3′
Fine	1.2′ - 2.2′	approx. 1.5′
Critical	0.5′ - 1.2′	approx. 1′

2) The contrast between the brightness of the task and that of its background. This is defined by $c = (B_1\text{-}B_2)/B_1$, where B_1 is the brightness of the background and B_2 that of the task, which is assumed to be darker than the background). For convenience, common contrasts are also tabulated in *table II.*

Table II. Classification of contrast **c** between task and background.

Classification	Value of contrast c	
	Limits	Average
Good	0.6 - 1.0	0.8
Fair	0.3 - 0.6	0.4
Poor	0.15 - 0.3	0.2
Very poor	< 0.15	0.1

As far as the effect of the lighting is concerned, it is not the illumination (in lux) that determines the facility of perception, but the brightness level, which, apart from the illumination, is also governed by the reflection factor of the background, and in a review of this kind it is usual to assume one particular reflection factor: in this case let us take 0.9. *All illumination levels mentioned in the following will thus relate to this reflection factor.* For tasks in which the reflection factor of the background is less, higher illumination levels are to be taken in proportion.

As regards the ease of performance of visual tasks, different investigators have made use of different criteria: Luckiesh and Moss [1]) and Waller [2]) assume certain factors to indicate how "far" the task lies above the threshold of visibility (as delineated in diverse ways). Efforts can also be made to employ as a measure of the ease of performance the degree of fatigue after a certain period of observation, in the manner discussed in a previous article in this review [3]).

Weston, in his investigations, adopts as a measure of performance the time taken for the observation in conjunction with the percentage of errors made [4]) and this conception appears to us very attractive, since it entails data which are not only capable of easy measurement but which have a very obvious practical value for expressing the ease of performance of a task; the arguments put forward in the following paragraphs are therefore based on Weston's experiments.

For a clear understanding of the problem it should be pointed out that the salient features of detail-size and contrast are in themselves not enough fully to characterize a given task. In general, it is moreover necessary to take into account the period of time during which the observations are made, whether these periods are broken by resting or waiting time and, again, whether the task involves any element of responsibility and so on. A table of recommended illumination levels compiled from observations relating to tasks entailing different sizes of detail and contrast values should therefore also indicate the circumstances, in accordance with the above. Then, when the appropriate illumination level for a given task is selected from the table, any differences in the factors referred to can be taken into account as far as possible by means of positive or negative allowances on the recommended level.

There is also another point of view, namely that the characteristics of the task and the ease with which it is performed, when examined closely, cannot easily be discriminated from each other, for the features of the task may be regarded as a measure of the difficulty or ease of performing it and there can be little sense in making a distinction between the degree of difficulty and the ease of performance of a task. The only significance of such a distinction is that the first must be looked upon as an independent variable and the latter as a dependent variable (with the illumination as parameter). This is clearly seen from the duration of the observation (rate of observation) introduced in the article referred to in footnote [3]) as characterising the task itself: Weston, however, employs it to characterise the performance of the task.

Weston's measurements: the concepts "performance" and "relative performance"

In Weston's experiments his subject was asked to examine charts showing a large number of open rings (Landolt's rings) with the slit directions distributed at random (*fig. 1*). The task consisted

[1]) M. Luckiesh and F. K. Moss, Visibility, its measurement and importance in seeing. J. Frankl. Inst. **220**, 431-466, 1935.
[2]) A. Waller, "Zichtbaarheid", diss, Utrecht 1945.
[3]) A. A. Kruithof and H. Zijl, Illumination levels in offices and dwellings. Phil. Techn. Rev. **8**, 242-248, 1946. The considerations regarding fatigue mentioned in this article were based mainly on measurements by M. Luckiesh and F. K. Moss. Trans. Ill. Eng. Soc. **34**, 571, 1939.
[4]) H. C. Weston, Industrial Health Research Report No. 87, H. M. Stationery Office, London, 1945.

in identifying and crossing off on each chart rings of a given orientation.

The detail to be observed — the slit in the ring — is of a given size and a given contrast on each individual chart and Weston expressed the performance of the eye for a given task as the quotient of the accuracy of the result (i.e. the ratio of rings marked correctly, to the total number of rings of the given orientation) *and the time required by the operator to determine the orientation of one ring.*

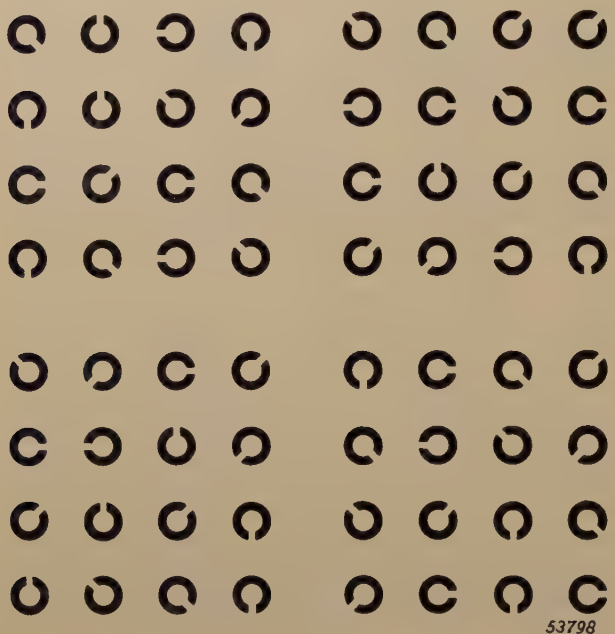


Fig. 1. Part of one of Lansolt's ring-charts, as used by Weston in his experiments. The diameter of the rings and therefore also the size of the slit (i.e. the detail to be observed) varies from one chart to another. The contrast, determined by the difference in reflection factor of the rings and the paper on which they are printed, also varies among the different charts. The rings are printed in eight different positions and the subject is required to mark off all rings having a certain orientation, being allowed as much time as he may deem necessary. This period of time, in conjunction with the number of rings overlooked, serves as a measure of the performance. The tests as carried out were in series of 1 minute duration with intermediate rest breaks of about $^1/_2$ minute, covering a total working period of $1^3/_4$ hours.

This quotient was taken by Weston to be the performance; he measured the average performance of a number of subjects, as a function of the illumination level for different sizes of detail and contrast. Some of his results are reproduced in *fig. 2.*

In this way, in principle the effect of the illumination on the performance of a task is known and it only remains to establish a standard of qualifications. In this connection Weston introduced the concept "relative performance": the curves in fig. 2, each of which refers to a particular task, do not rise indefinitely, but begin to drop at very high illumination levels (> 20,000 lux, approx.) due to the fact that the disability glare begins to take effect. There is therefore a maximum performance for every task, and the relative performance is the ratio of the actual to the maximum possible performance. Our appraisal of an illumination level will thus have to be higher as the maximum performance for the task in question is more closely approached, i.e., as the relative performance more nearly reaches unity. The standard, then, will have to establish a relationship between the qualifications "sufficient", "good" etc. and certain relative performance values. This point will be referred to later.

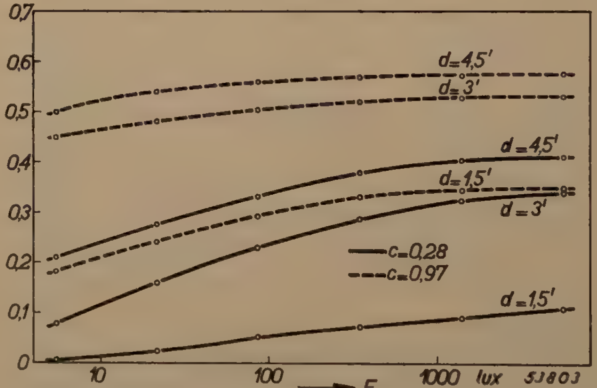


Fig. Performance as a function of the illumination E in lux, according to Weston. Each case refers to a particular task, i.e. size of detail d and contrast c. (In Weston's tests each contrast value was based on a different reflection factor of the background, i.e. the paper on which the rings were printed; in view of our remarks in the previous paragraph, we have converted Weston's illuminatoin values to agree with a constant reflection factor of 0.9.)

Reshaping Weston's data into a lighting table

In measurements such as those carried out by Weston there is bound to be a certain amount of deviation among the results, even though these be the averages taken from groups of different observers. Obviously, the differences thus arising

[5]) The performance of a task usually involves both an observation and a subsequent action (in the above case the marking of the ring identified). Both phases occupy a certain amount of time and they both present an opportinuty for making a mistake. Now, in order to obtain a true measure of the visual efficiency — this being our ultimate object — the errors in the action and the time taken to complete it should not be included. Weston therefore made a separate record of the time taken in marking a ring, and deduced this from the total time measured. The task in question is so simple (this being the reason why it was selected) that a correction for errors in the action are not necessary. In any case, an error in the performance of the task can consist only in the omission of a ring (the marking of a ring pointing in the wrong direction, in which case it would not be known whether the fault lies in the observation or in the action, was such a rare occurrence that it could be neglected).

between the various quantities cannot be allowed to pass into the final recommendations to be issued to lighting engineers, and fig. 2 gives a graphical representation of performance versus illumination level as smoothed by Weston.

Since in practical applications of the data the particular task is in each case the starting point, concerned a different set of such curves is used, see *fig. 3*.

In this manner the irregularities in the functions are smoothed out (thus guaranteeing more reliable interpolation for any required contrast value), whilst ensuring that the curves also tally with known data concerning the threshold of vision.

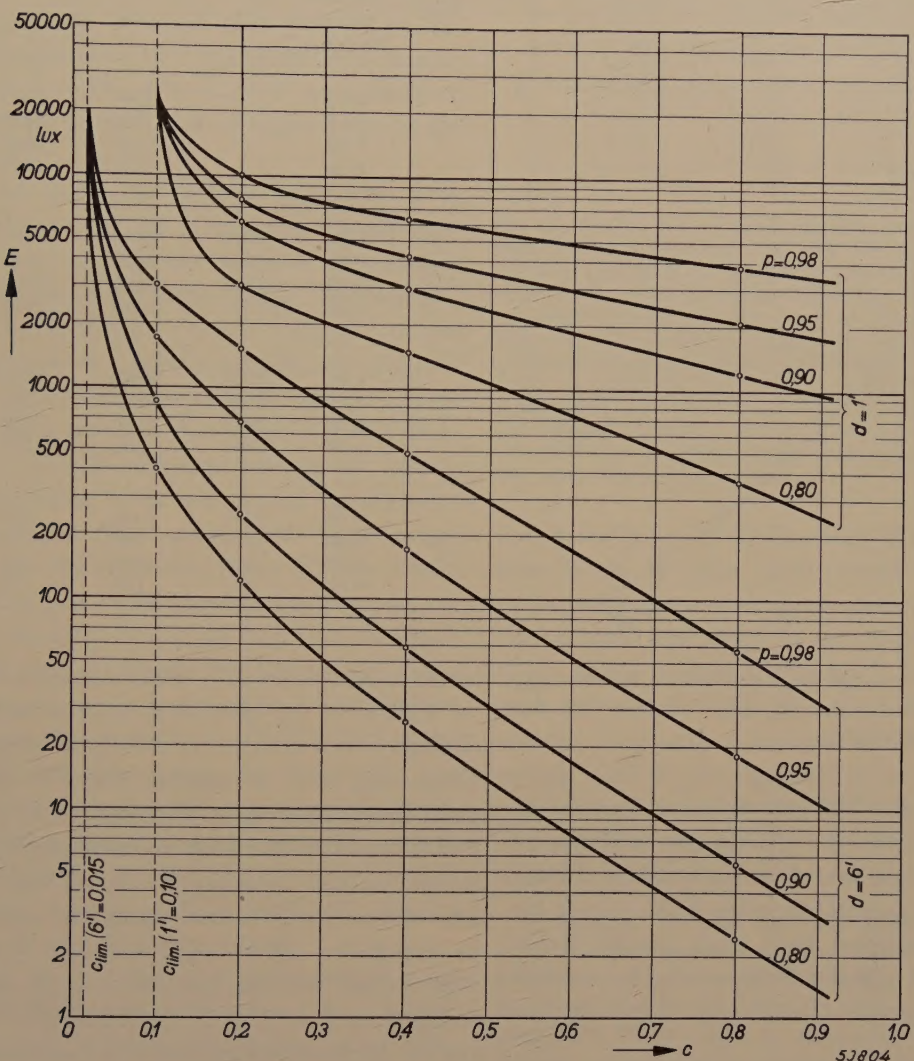


Fig. 3. Illumination E in lux required to ensure a given relative performance p on the basis of a given detail size d plotted against the contrast c. In this manner it is possible to "smooth out" and interpolate Weston's data in regard to the effect of the contrast. The curves are also subject to the condition that each group relating to the same detail size must approach the vertical line corresponding to the least perceptible contrast c_{lim}, for that detail size.

it is desirable from the point of view of easy interpolation also to smooth out the ratios in regard to the effects represented by the parameters, viz. size of detail and contrast, which means the removal of irregularities in the spacing of the curves shown in fig. 2. This has been done by plotting, as a function of the contrast, the illumination required to ensure a certain relative performance, thus producing a family of curves with the relative performance as parameter; for every size of detail Even though the illumination level be raised to the point of disability glare, it is not possible to see an object of a given size if the contrast between that object and its background lies below a certain minimum value, and in *fig. 4* [6]) this minimum is shown plotted against the size of the object. At such very high illumination levels

[6]) H. Siedenhof, Das Licht **11**, 35, 1941. A. Kühl, Z. Instrumentenkunde **60**, 292, 1940.

the effect is that each of the groups of curves in fig. 3, relating to a certain size of detail, must approach the vertical line on which the contrast is at its corresponding minimum value, for, if tasks are to be undertaken at such low contrast values, a very high illumination will be needed to yield even the smallest performance.

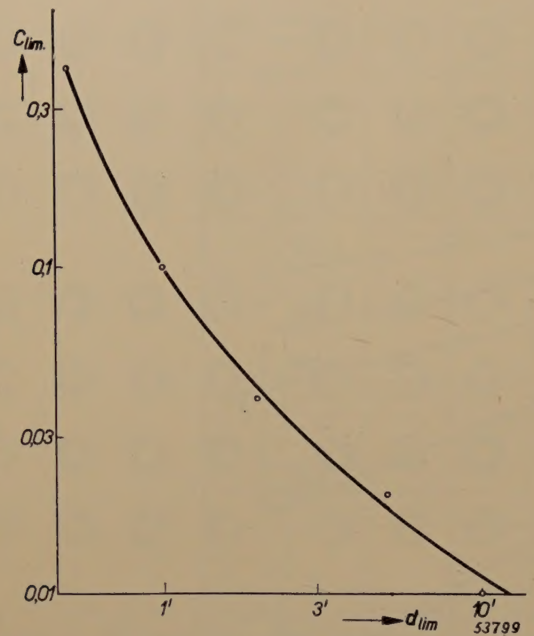


Fig. 4. Relation between the least perceptible contrast c_{lim} and smallest perceptible detail d_{lim} (derived from data by both Siedentopf and Kühl).

The data have also been smoothed out as far as the detail size is concerned (with the contrast as parameter for the groups of curves) and here, too, it has been found possible to correct the curves by enforcing the condition that each group for a particular contrast value will approach the vertical line at the appropriate threshold of perception of detail.

In this way the illumination levels shown in *table III* were obtained.

Stages of difficulty of task and performance

To ensure reliable interpolation once more, the successive columns (and lines) of the table should refer to tasks the difficulty of which increases in roughly constant steps. From table III it will be seen that, as far as this requirement is concerned, the gradations of detail size and contrast adopted in tables I and II answer the purpose very well. For example, if we proceed from the illumination levels specified for a task: detail size d = 1.5′, contrast c = 0.2, the illumination value required to ensure a specified relative performance will be seen to

Table III. Illumination in lux required to ensure given values of the relative performance of tasks involving different values of contrast **c** and detail size **d** (reflection factor of background 0.9). In comparison with Weston's original experimental results, the illumination levels have been smoothed out, partly with the aid of fig. 3.

Size of detail d	Contrast c / Relative performance p	0.1	0.2	0.4	0.8
1′	0.98		9900	6300	3800
	0.95		7500	4300	2050
	0.90		5400	2900	1200
	0.80		3100	1500	360
1.5′	0.98	9900	6600	3900	1600
	0.95	8100	4500	2400	750
	0.90	5700	3300	1500	370
	0.80	3300	1650	610	97
3′	0.98	5800	3600	1600	260
	0.95	4100	2250	780	110
	0.90	2500	1300	320	34
	0.80	1300	550	130	12
6′	0.98	2900	1600	480	57
	0.95	1700	700	170	19.5
	0.90	880	260	59	5.4
	0.80	420	120	26	2.6

increase just as much [7]) when changing the task to d = 1.5′, c = 0.1 (one step to the left) as when changing to d = 1′, c = 0.2 (one step upwards). Expressing this in another way, it may be said that the reduction in contrast from c = 0.2 to c = 0.1 renders the task more difficult to the same extent as the decrease in detail size from d = 1.5′ to d = 1′. If we now apply the same argument to a task d = 3′, c = 0.2 and d = 6′, c = 0.2, it will further be seen that the steps in the difficulty factor from d = 3′ to d = 1.5′ and d = 6′ to d = 3′ are for all practical purposes the same as from c = 0.2 to c = 0.1: in other words the three steps of the element of difficulty lying between the four grades of detail size d are practically the same.

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[7]) In all these arguments it should be borne in mind that there is no object in striving towards too high a degree of accuracy when making comparisons between illumination levels. Owing to the fact that individual differences in visual performance are found to be considerable even for such quantities as contrast sensitivity and visual acuity, which are easily measured, variations up to 30% between anticipated and actual illumination need not be regarded as serious. In the ultimate levels recommended it is probable that greater discrepancies will occur as a result of subjective appraisal of the allowances, which latter, as mentioned above, are required to counterbalance numerous differences between the actual circumstances governing both a particular task and the type of task as selected from the table.

This may be verified by a comparison of the illumination levels in the columns for contrast $c = 0.4$ and $c = 0.2$, $c = 0.8$ and $c = 0.4$. Further, the three difficulty steps between the four gradations of contrast are not only aproximately equal, but also approximately the same as the steps corresponding to the detail size. There remains only the question whether the four stages in the relative performance p have been suitably chosen; in this case it is required that the transition from a specified value of p to the next higher stage shall in each instance represent a step of a given size in the relative difficulty factor [8]).

To check this point the obvious procedure is to calculate the factor (g) by which the illumination should be increased in order to raise the relative performance to the next higher stage. Admittedly, this factor is by no means a direct measure of the difference between the difficulty in the one stage of performance and the next, as is borne out at once by the fact that for a given performance step, say from 0.80 to 0.90, entirely different increment factors for the illumination level are found in different parts of the table. The same holds good when calculating from the table the factor (f) by which the illumination has to be increased to compensate for one step in the difficulty of the task (i.e. reduction of contrast or size of detail), at a constant value of p. Curiously enough it is found that both factors depend only on the illumination level taken as the starting point for the steps in difficulty and performance respectively and, owing to this fact, we are entitled to draw a comparison, in respect of any initial level, between the factor g, corresponding to one step in performance, and factor f which relates to one step in contrast.

Accordingly, we find that the performance steps 0.98/0.95, 0.95/0.90, 0.90/0.80 are, on an average, equivalent to 0.63, 0.59 and 0.65 times the value of one contrast step; the four performance stages 0.98, 0.95, 0.90 and 0.80 selected are thus quite equally spaced.

If the average factor f as calculated from the table be plotted as a function of the illumination level, there will naturally be a considerable scattering of the points, but a smooth curve drawn through these will give the average factor f as shown in *fig. 5*. These average factors enable us to apply a final correction to table III: what we have actually done is to equate the illumination levels relating to the four equally difficult tasks in the diagonal $d = 6'$, $c = 0.1$ to $d = 1'$, $c = 0.8$, with the average values

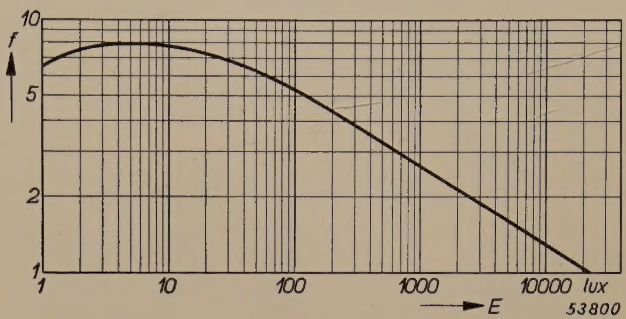

Fig. 5. Factor f by which the illumination level must be increased in accordance with table III to maintain the same relative performance when the difficulty of the task is increased one step. It appears that this factor, within quite reasonable limits, depends only on the starting level. The curve has been drawn as a smooth line through the somewhat scattered points relating to the values of f calculated from the table. It meets the line $f = 1$ at about 20 000 lux, and this agrees with the established fact that vision does improve any further at levels beyond 20 000 lux (apart from tasks the difficulty of which is less than one stage removed from the threshold of perception).

found for these tasks in table III (correcting the four levels so that their ratios agree with the average factors g as derived above); we have then calculated the levels for all other tasks by means of the factor f, as read from fig. 5. At the same time, each calculated value has been rounded off in a manner frequently employed in illuminating engineering, viz. to the nearest of a series of values (excepting factors of 10) [9]): 1 - 1.25 - 1.6 - 2.0 - 2.5 - 3.2 - 4.0 - 5.0 - 6.3 - 8.0 - 10. The standarised table thus obtained is given below (*table IV*).

In the same way that this table is derived on the basis of Weston's definitions end experiments, it would also be possible to prepare a table according to the methods of Luckiesh and Moss, or Waller, alluded to in the opening paragraphs [10]). It might be interesting to see whether the different tables could be brought into line with each other, but here we cannot go into this matter any further.

Practical uses of the lighting table

It may now be asked to what interpretations as "sufficient", "good", etc. the above stages for the relative performance 0.80, 0.90, 0.95, 0.98 refer. By assuming a particular task and making a comparison between the relative data (inter alia

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[8]) This again illustrates the fact that if attempts are to be made to discriminate between „difficulty" and "performance" ,it is merely a question of the choice of dependent and independent variables: it would be quite feasible to include the requirement of a certain relative performance in the delineation of the task and say that the latter becomes more difficult as the demands in respect of the level of performance are made more stringent.

[9]) As an approximation, these values form a geometrical series in the ratio of $\sqrt[10]{10}$ and thus divide the factor 10 into 10 equal intervals.

[10]) *Note at time of going to press.* More recent research in this field, introducing slightly different definitions, may be found in E. Simonson and J. Brozek: Effects of illumination level on visual performance and fatigue, J. Opt. Soc. Americ. *83*, 383-397, 1948 (No. 4).

Table IV. Illumination in lux required for four values of the relative performance of tasks involving different contrast **c** and detail **d** (reflection factor of the background = 0.9). The illumination values given differ from those in table III in that they are calculated with the aid of the smoothed-out factor **f** in accordance with fig. 5 and subsequently rounded off as explained in the text.

Detail size d	Relative performance p \ Contrast c	0.1	0.2	0.4	0.8
1′	0.98		10000	6300	4000
	0.95		8000	4000	2000
	0.90		5000	2500	1000
	0.80		4000	1600	500
1.5′	0.98	10000	6300	4000	1600
	0.95	8000	4000	2000	800
	0.90	5000	2500	1000	320
	0.80	4000	1600	500	100
3′	0.98	6300	4000	1600	500
	0.95	4000	2000	800	160
	0,90	2500	1000	320	50
	0.80	1600	500	100	12.5
6′	0.98	4000	1600	500	100
	0.95	2000	800	160	25
	0.90	1000	320	50	6.3
	0.80	500	100	12,5	1.6

from the article mentioned in note [3]), it would be possible to give a general answer to the effect that a relative performance of, say 0.90 to 0.95, may be considered "good": this is in fact the standard suggested by Weston. In actual practice, however, the question and its answer are hardly relevant, for, with a little experience, the value of the relative performance can be employed directly as an indication of the quality of the lighting system, thus avoiding the detour by way of the descriptions "good", etc. employed in the introduction merely to clarify the point at issue.

In continuation of the remarks contained in the opening paragraphs, we now have the means of recommending a certain relative performance p to be the ultimate object under any given set of economic conditions. Conversely it will be useful to ascertain what average performances can be realised on the basis of the lighting tables now in use in various countries. It will be found, for example, that the German (pre-war) tables correspond to $p = 0.80$ to 0.85 for a task of average difficulty, and the latest American tables to $p = 0.95$ to 0.98. For very easy tasks the illumination levels recommended in the tables of every country concerned correspond to performances of roughly $p = 1$. This is not difficult to understand, since the highest relative performance values can be achieved for easy tasks at relatively low illumination levels. Performance can then no longer be a criterion of the required illumination and other considerations, such as a bright atmosphere in the place of work, will be brought forward as the reason for the recommendation of much higher illumination levels than those specified in table IV for such tasks.

If the lighting table is to be employed in connection with industrial tasks it will be advisable to remember that the differences in "relative performance" with respect to various illumination levels do not correspond in general to equally large differences in production figures. The concept "performance" employed in this article is solely a measure of the ease of performance of the visual element of a task: in a practical task involving more or less complex actions in step with visual observation (in accordance with note [5])) the influence of the illumination on the final result, i.e., the "production", may be appreciably less than its effect on the "visual peformance", since the time needed for the manual part of the task and the corresponding risk of error are independent of the illumination level.